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Computational Analysis of Indoor Thermal Comfort in a Terraced Family House with Thermal Insulation

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ABSTRACT Computer simulations are used to assess the impact of thermal insulation on the transfer of heat and moisture in the exterior walls of residential buildings. The effects of internal and external thermal insulation on a room in a terraced family house are compared using the COMSOL Multiphysics software package, evaluating the influence of the placement of expanded polystyrene thermal insulation on the distribution of heat and moisture in the external wall while monitoring the indoor air temperature during the heating and cooling regimes. The internal thermal insulation is more efficient in terms of room heating, while the external insulation is preferable in reducing the risk of the condensation water vapor within the wall. The efficiency of heating the room to 20°C increased by 12% when internal thermal insulation was added to the walls, compared to heating without insulation. The maximum value of relative humidity in the critical wall section decreased by 10% when external thermal insulation was added. Implementing internal thermal insulation needs the right choice of insulation material and its installation to prevent air leakage. The results suggest that the proper selection of the placement of the thermal insulation is critical for optimizing the thermal performance and reducing moisture-related problems in residential buildings.

INDEX TERMS COMSOL Multiphysics, cooling of a room, expanded polystyrene, external thermal insulation, heat transfer, heating of a room, internal thermal insulation, moisture transfer, numerical simulation, terrraced family house, thermal comfort.

I. INTRODUCTION

Shortages and increases in energy prices for heating or cooling residential buildings are currently faced by many countries. Finding ways to achieve the required indoor thermal comfort and suitable hygienic conditions while simultaneously reducing energy consumption is crucial.

Generally speaking, the materials of older buildings are often less able to accumulate heat, thus causing rapid cooling of the interior. Therefore, one of the challenges in designing energy-efficient buildings is to optimize their thermal performance using suitable building materials and thermal insulation. In this regard, many studies cover the effect of thermal insulation on energy consumption and thermal comfort [1], [2]. Covering the exterior walls of a building with thermal insulation is a key factor affecting the heat transfer between the indoor and outdoor environments. However, different types of insulation materials and methods of incorporating them into the walls can significantly influence the buildings' temperature distribution and energy consumption. Appropriate thermal insulation should help maintain the desired interior air temperature, considering the given location's climatic conditions [3], [4].

The optimal choice of the type of insulation depends on various factors, such as the climate, the design of the building, and economic feasibility. Several materials can be used as thermal insulation for buildings. Some common materials include mineral wool, sheep wool [5], [6], expanded polystyrene (EPS) [7], extruded polystyrene (XPS), polyurethane foam, and glass fiber [8]. Also, the effects of the combination of the insulation and other materials are studied. For example, the influence of thermal insulation and phase change materials on the energy consumption for buildings' indoor thermal comfort has been tested by [9]. [10] focused on comparing thermal insulation materials and steady state heat transfer performance of light-frame wood structure walls. Paper [11] aimed at assessing the thermal performance of contemporary ceramic blocks with a complex internal geometry in building envelopes.

Diffusion resistance is also an important factor that needs to be considered when choosing a thermal insulation material [12]. Materials with open-air cavities, such as mineral wool, aerated concrete, and ceramic bricks, have a low diffusion resistance. In contrast, glass, plastic, metal, and expanded polystyrene have high diffusion resistance. These materials have closed pores and thus do not allow air and water vapor to pass through.

It is also essential to determine the optimal thickness [13], [14], [15], and location of the thermal insulation materials in the wall of the building. External thermal insulation can provide several benefits, including improved energy efficiency, reduced heat loss, and increased thermal comfort. It can also help protect the building from external weather conditions and moisture damage. However, it has drawbacks, such as its higher initial costs, maintenance costs, and aesthetic value. On the other hand, internal thermal insulation can be less expensive than external insulation, and it can be easier and less disruptive to install. However, internal insulation must be properly selected so as not to limit the usable space inside the building, and to have a similar effect at reducing heat loss as external insulation. In addition, its correct installation is necessary so as to not increase the risk of moisture and mold buildup inside the walls.

The influence of the position of the thermal insulation in a building's exterior walls on the indoor thermal comfort and energy consumption is evaluated in work [1], where four typical models of residential buildings in Chongqing were studied, with different positionings of the layers of thermal insulation in exterior walls. Authors [16] compared the transfer of heat and moisture in internal and external wall insulation configurations. The indoor thermal comfort hours as well as the energy consumption of the cooling and heating of each model were obtained using a simulation tool. The effect of the internal and external wall insulation on the energy efficiency of the building with compartmental and intermittent energy-consuming methods is studied by researchers [17]. Work [7] is focused on the study of the dynamic effect of external insulation on the indoor thermal environment and energy consumption. Authors [18] present a comparative numerical assessment of external and internal thermal insulation for an intermittently air-conditioned building. The energy consumed for cooling is used to evaluate the exterior wall thermal insulation configurations. Study [19] is focused on the analysis and evaluation of the increase of stress in the external walls and adjacent structures caused by non-forced effects of temperature changes after the application of internal insulation.

As described above, it is crucial to study the effects of the building's outside and internal thermal insulation. For this purpose, the methods used can combine experimental testing and theoretical calculations. In addition, computer simulations can solve complex multiphysics problems in building constructions by defined numerical methods. They can significantly help in assessing the suitability of the design of building modifications concerning specific buildings, taking into account the requirements of the economic feasibility of the given technical solution, the required thermal comfort of the interior, hygienic conditions, and the aesthetic aspect of the architectural design solution.

For an immediate assessment of the thermal behavior of an object, thermographic methods can be applied. General signal and image processing methods used in engineering, architecture, and medicine can be used to process and evaluate the output data [20], [21].

In this study, we follow up on previous studies focused on heat transfer in buildings concerning their construction and outdoor climatic conditions [22], [23], [24]. We used the Heat Transfer Module of the COMSOL Multiphysics software package [25] to solve the non-stationary heat and moisture transfer in the external walls of a room that is part of a terraced family house according to Fig. 1. The aim is to assess the health risk concerning compliance with the required thermal comfort of the interior, the possibility of the formation of mold due to increased surface moisture of the walls, and the risk of damage to the building structure due to the condensation of water vapor in the exterior wall. We compare the influence of the composition of the external wall on the temperature and moisture profiles in the tested building construction and the evolution over time of the interior air temperature under the specified winter conditions. We also analyze the sensitivity of the results to the temperature of the internal heat sources. We performed an experimental assessment of the temperature distribution of the surface walls of the tested room using a thermal camera.

II. METHODS

Computer simulations of non-stationary heat and moisture transfer were performed by COMSOL Multiphysics 5.3 (COMSOL, Stockholm, Sweden). The results were verified on a real object, the assessed room, by the records taken by the mobile thermal camera Seek Thermal Pro. The subsequent evaluation and graphical processing of the output data and humidity assessment were performed using the MATLAB 2022b (MathWorks, Massachusetts, USA) computational environment.

A. HEAT TRANSFER IN A BUILDING

Numerical simulations of the non-stationary heat transfer between the interior of a house and the outdoors are based on the governing Eq. (1) [25], [26]:

$$\nabla\left(-k\nabla T\right)+\varrho c_p v\nabla T+\varrho c_p\frac{\partial T}{\partial t}=\Phi \qquad (1)$$

where T is the thermodynamic temperature, $[\mathrm{K}]$, v is the velocity of the fluid, $[\mathrm{m/s}]$, ϱ is the density, $\left[\mathrm{kg/m^3}\right]$, c_p is

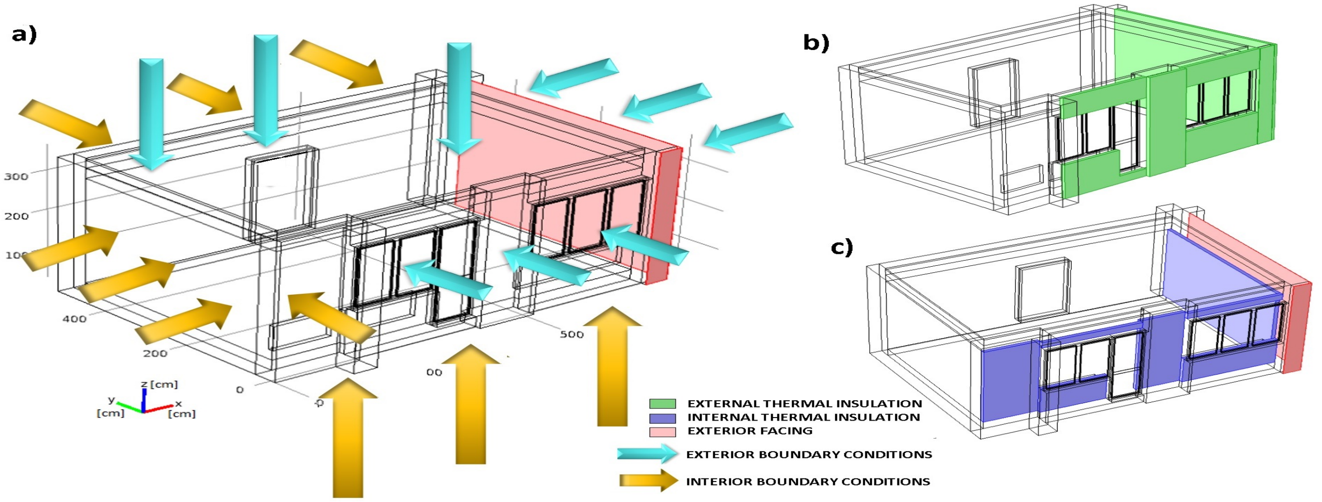

FIGURE 1. Geometric sketch of studied models; a) a room without thermal insulation, b) a room with external thermal insulation, c) a room with thermal insulation in its interior. The arrows in the model without thermal insulation indicate the environment inside and outside the house.

the specific heat capacity, $[\mathrm{J/(kg \cdot K)}]$, and Φ is the rate of generation of inner heat per unit volume, $\left[\mathrm{W/m^3}\right]$.

The heat flux density during heat transfer at the interface between the surface of solid building materials and ambient air is described by the boundary condition:

$$q_s = h\left(\theta_i - \theta_{si}\right) \tag{2}$$

where q_s is the heat flux density, $\left[\mathrm{W/m^2}\right]$, h is the heat transfer coefficient, $\left[\mathrm{W/(m^2 \cdot K)}\right]$, θ_i is the fluid temperature, $[^\circ\mathrm{C}]$, and θ_{si} is the temperature of the inner surface of the solid material, $[^\circ\mathrm{C}]$.

The radiant flux from a surface of a building to the ambient environment is described by the Stefan–Boltzmann law:

$$q_r = \epsilon\sigma\left({T_s}^4 - T_{amb}^4\right) \tag{3}$$

where q_r is the radiant flux density, $\left[\mathrm{W/m^2}\right]$, σ is Stephan-Boltzmann constant, ϵ is the surface emisivity, $[-]$, and T_s is the surface thermodynamic temperature, $[\mathrm{K}]$, T_{amb} is the ambient thermodynamic temperature, $[\mathrm{K}]$.

The thermal stability of different buildings can be compared according to the value of the time constant, which is an indicator of the time required for the interior temperature to stabilize, assuming a linear course of the monitored thermal process.

B. DIFFUSION OF VAPOR THROUGH BUILDING MATERIALS

The concentration of moisture in the air is an important factor in the indoor environment of a building. If the building's walls are permeable to water vapor contained in the air, water vapor diffuses through the external walls [27]. The stationary diffuse flow of water vapor through the walls can be expressed by Eq. (4):

$$\vec{g_v} = -\delta_p \cdot \nabla p_v \tag{4}$$

where δ_p is the water vapor diffusion coefficient, $[\mathtt{s}]$, ∇p_v is the partial pressure gradient of the water vapor, $[\mathtt{Pa}]$, and $\vec{g_v}$ is the water vapor diffusion flux density, $[\mathtt{kg/(m^2 s)}]$.

In a layered building structure, the diffusion resistance should decrease in the space from the inner to the outer surface [27].

The intensity of water vapor transfer through the wall depends on its diffusion resistance value. The degree of tightness of the building material against diffusing water molecules can be determined using the coefficient of the water vapor diffusion resistance (μ), which indicates an increase of the diffusion resistance of the building compared to the air.

The equivalent air layer thickness (Sd) is the diffusional equivalent of the air layer thickness that creates a barrier for water vapor diffusion. A higher value of Sd causes higher diffusional resistance and vice versa. For a wall consisting of multiple layers of material, Sd can be determined according to the following equation [28], [29]:

$$Sd = \sum_{i=1}^{n} \mu_i \delta_i \tag{5}$$

where δ_i is the thickness of the ith layer, $[\mathtt{m}]$, and μ_i is the water vapor diffusion resistance factor of that layer, $[-]$.

One takes $Sd \leq 0.5$ m for a water diffusion-open material, and $Sd > 0.5$ m for a diffusion-blocking material. If $Sd \geq 1500$ m, then the material is diffusion-proof.

In the COMSOL Multiphysics interface, computer simulations of non-stationary heat and moisture transport in building materials are based on the numerical solution of Eqs. (6)–(7) [25]:

$$\left(\varrho\, c_p\right)_{eff} \frac{\partial T}{\partial t} - \nabla\left(k_{eff} \nabla T + L_v \delta_p \nabla\left(\phi p_{sat}\right)\right) = Q \tag{6}$$

$$\xi \frac{\partial \phi}{\partial t} - \nabla\left(\xi D_w \nabla \phi + \delta_p \nabla\left(\phi p_{sat}\right)\right) = G \tag{7}$$

where $\left(\varrho\, c_p\right)_{eff}$ is the effective volumetric heat capacity at constant pressure, $\left[\mathtt{J}/\left(\mathtt{m^3.K}\right)\right]$, T is the thermodynamic

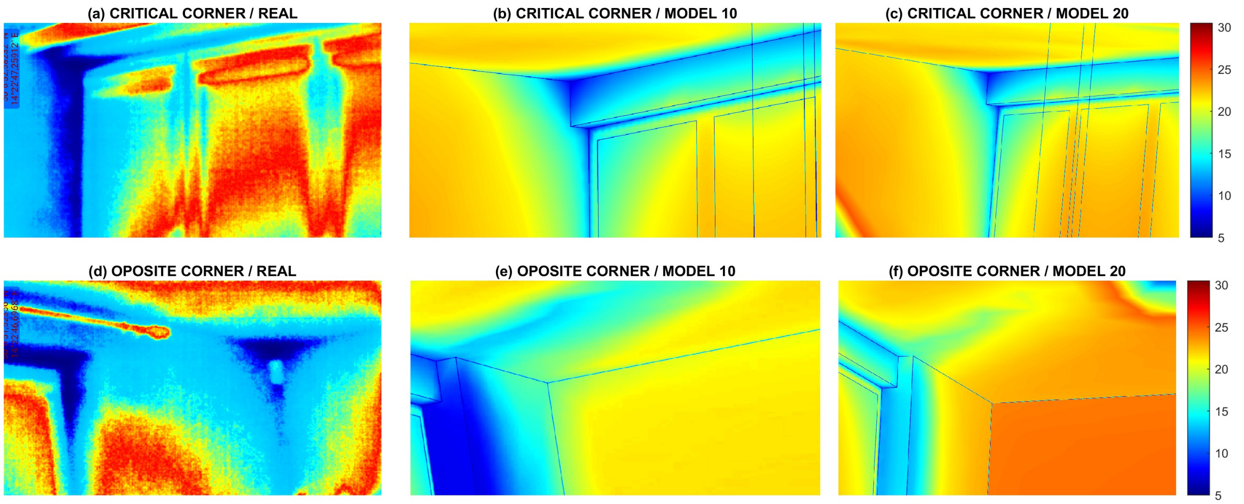

FIGURE 2. Comparison of the surface temperature in the critical and the opposite corner of the outer wall of the room determined by a thermal camera and computer simulation including (a) the temperature in the critical corner of room recorded with a thermal camera, (b,c) results of computer simulation with the temperature in the neighbour room 10 and 20 deg.C., respectively, (d) the temperature in the opposite corner of room recorded with a thermal camera, (e,f) results of computer simulation with the temperature in the neighbour room 10 and 20 deg.C., respectively.

TABLE 1. Material properties used for computer simulations.

Material	Thermal conductivity (k) [W/(m.K)]	Specific heat capacity (c_p) [J/(kg.K)]	Density (ϱ) [kg/m^3]	Emisivity (ϵ) [-]	Diffusion coefficent (D_w) [m^2/s]	Water vapor diffusion resistance factor (μ) [-]	Water content (w) [kg/m^3]
Glass	0.940	840	2600	0.940	-	-	-
Wood	0.180	2510	400	0.940	-	-	-
Brick	0.800	900	1800	0.850	$1.2 \cdot 10^{-8}$	9.5	130
Exterior facing	0.800	900	2000	-	$1.2 \cdot 10^{-8}$	9.5	130
Mineral plates	0.050	850	200	-	-	-	-
Polystyrene	0.035	1250	30	-	$4 \cdot 10^{-9}$	60	0.18
Lime plaster	-	-	-	0.850	-	-	-
Aluminium	237	900	2700	-	-	-	-
Argon	1.178	520	1.782	-	-	-	-
White vanish	-	-	-	0.870	-	-	-

temperature, [K], k_{eff} is the effective thermal conductivity, [W/(m.K)], L_v is the latent heat of evaporation, [J/kg], δ_p is the vapor permeability, [s], ϕ is the relative humidity,[$-$], p_{sat} is the vapor saturation pressure, [Pa], Q is the heat source, [W/m^3], ξ is the moisture storage capacity, [kg/m^3], D_w is the moisture diffusivity, [m^2/s], and G is the moisture source, [kg/m^3].

The convective moisture flux on the boundary between the solid material and the ambient liquid can be described by (8):

$$q_O = \beta \left(\phi_{amb} p_{sat} \left(T_{amb}\right) - \phi p_{sat} \left(T\right)\right) \quad (8)$$

where β is the moisture transfer coefficient, [s/m], p_{sat} is the vapor saturation pressure, [Pa], ϕ_{amb} is the relative humidity of the ambient liquid, [$-$], T is the thermodynamic temperature, [K], and T_{amb} is the ambient thermodynamic temperature, [K].

A geometric sketch of the tested room with the considered location of the thermal insulation inside and outside the house is shown in Fig. 1. It is assumed that the room is located on the 2nd floor, under the roof. Its left wall (when viewed from the outside) is shared with the neighboring house. The right wall is surrounded by the outdoors. The size of the room is 450 cm × 720 cm × 265 cm. The thermophysical parameters of the elements of the model are summarized in Table 1.

From the point of view of ensuring the required temperature and humidity conditions of the interior of the house and reducing the risk of damage to the walls of the building structure, the critical area is primarily the left corner of the room (critical corner), which is at the interface of the front wall, the left side wall, and the ceiling of the room (as seen from the interior of the house). A window on the room's front wall is near the critical corner. The outdoor environment surrounds the left side wall, the front wall, and the ceiling. Therefore, the critical corner is susceptible to damage due to the intensive transfer of heat and moisture between the interior and exterior of the house.

III. RESULTS

The results of this study include observations by the thermal camera and simulations presented in Fig. 2. Numerical

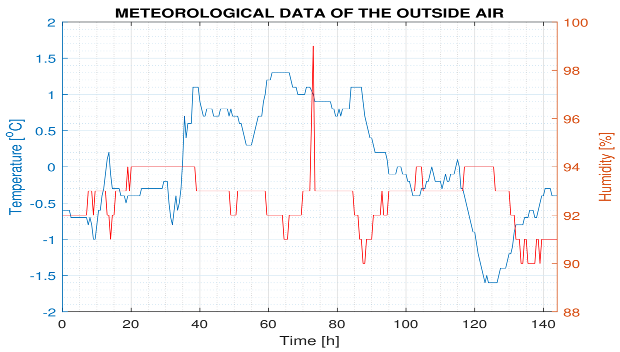

FIGURE 3. Temporal evolution of outdoor air temperature and humidity for five days prior to critical room corner temperature analysis.

calculations were experimentally verified in this way. The dataset recorded by simulations of surface temperatures in the critical corner of the room and the corresponding images recorded by the thermal camera are stored at the IEEE DataPort (http://ieee-dataport.org/11267) for further investigation. This repository also includes a video abstract of the paper.

A. COMPARISON OF THE MEASURED (BY A THERMAL CAMERA) AND SIMULATED SURFACE TEMPERATURES IN THE CRITICAL CORNER OF THE ROOM

The temperature distributions of the surface walls in the critical corner of the room are shown in Fig. 2. They were evaluated in winter. The interior was heated to achieve an air temperature of about 21°C. The average outdoor air temperature was about 0°C. The comparison was made using the Seek Thermal Pro mobile thermal recording camera and computer simulations by COMSOL Multiphysics (see Fig. 2) under the assumptions that the air temperature of the interior of the neighboring house was 10°C (Figs. 2b,e), respectively 20°C (Figs. 2c,f). With respect to the climatic conditions of the tested house location, the meteorological data of the development of the outdoor air temperature for a period of five days was included in the simulation as a boundary condition (Fig. 3). The simulation results were compared for 134 hours, which corresponds with the time of the photos taken with the thermal camera. The results are in good agreement, taking into account the accuracy of both methods and the simplifying assumptions of the constructed physical model of the studied object. The surface temperature in the critical corner of the room was determined by both methods to lie in a range of approximately 5°C–15°C. The surface temperature in the opposite corner was approximately 10°C–20°C if the supposed air temperature in the neighboring room was 10°C, resp. 20°C–23°C if the supposed air temperature in the neighboring room was 10°C.

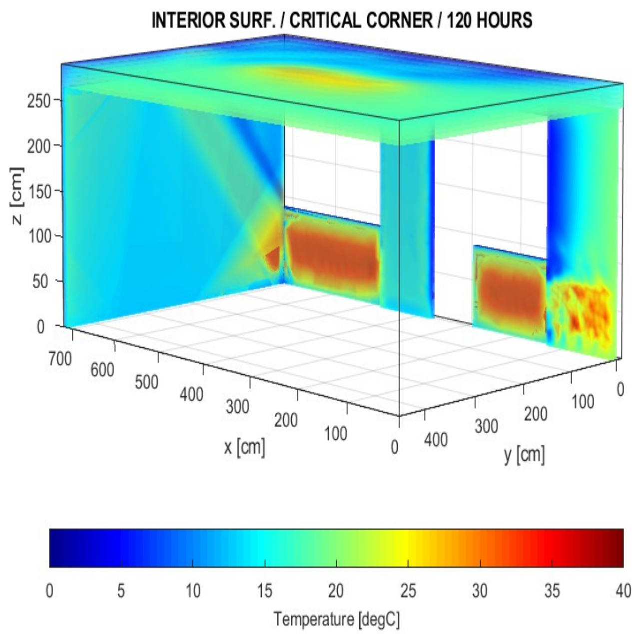

FIGURE 4. The 3D model of the temperature distribution in the walls of the room.

B. EFFECT OF THERMAL INSULATION ON THE TEMPORAL EVOLUTION OF HEATING AND COOLING THE ROOM

Computer simulations were performed for three models: one with thermal insulation with a thickness of 10 cm located inside the room, the other with this insulation located outside the house, and another for the same room but without thermal insulation. The aim is to assess the influence of thermal insulation on the temporal evolution of the heating and cooling of the room. A sketch of all the studied models is shown in Fig. 1.

An influence of the set radiator temperature was tested in the case of room heating. The results are compared for when the radiators are off and when the radiators are on with surface temperatures of 40°C and 50°C after five monitored days. The initial air temperature in the room was 10°C. The estimated air temperature of the surrounding rooms during the monitored period was 20°C. The distribution of temperature within the walls in the selected time 120 hours of heating is shown in Fig. 4. The air temperature distribution is shown in Fig. 5.

During cooling, the initial room air temperature was 20°C, and the air temperature of the surrounding rooms was 10°C. The outdoor temperature was -10°C, the heat transfer coefficient inside the house was 8 $\mathrm{W/(m^2 \cdot K)}$, the heat transfer coefficient through the exterior walls of the house was 25 $\mathrm{W/(m^2 \cdot K)}$. The room's air temperature and the surface temperatures of the exterior and side walls in the area of the critical and opposite corners of the room were evaluated.

Numerical methods for data resampling and polynomial smoothing were applied to process the output data because the node points of the numerical network in the assembled models were not evenly spaced.

TABLE 2. Results of simulations of the heating of the room. The time constant and final air temperature after five monitored days.

Monitored quantities	Without thermal insulation	Thermal insulation outside the house	Thermal insulation inside the room
HEATING OF THE ROOM: RADIATORS TURNED OFF			
Temperature of the air in the center point of the room [°C]:	15.4	16.5	16.9
Mean temperature of the air inside the room [°C]:	12.7	14.5	14.8
Time to achive 75% of the final air temperature [h]:	38.0	33.0	32.0
Time to achive 90% of the final air temperature [h]:	51.0	52.0	51.0
Time constant [h]:	70.0	76.0	81.0
HEATING OF THE ROOM: TEMPERATURE OF RADIATORS 40°C			
Temperature of the air in the center point of the room [°C]:	20.4	20.6	21.2
Mean temperature of the air inside the room [°C]:	19.2	20.0	20.3
Time to achive 75% of the final air temperature [h]:	35.5	31.0	31.0
Time to achive 90% of the final air temperature [h]:	47.0	46.5	46.5
Time constant [h]:	45.0	42.5	37.5
HEATING OF THE ROOM: TEMPERATURE OF RADIATORS 50°C			
Temperature of the air in the center point of the room [°C]:	22.2	22.3	22.8
Mean temperature of the air inside the room [°C]:	21.3	22.0	22.2
Time to achive 75% of the final air temperature [h]:	42.5	41.0	39.0
Time to achive 90% of the final air temperature [h]:	58.5	56.0	55.0
Time constant [h]:	35.0	34.5	31.0

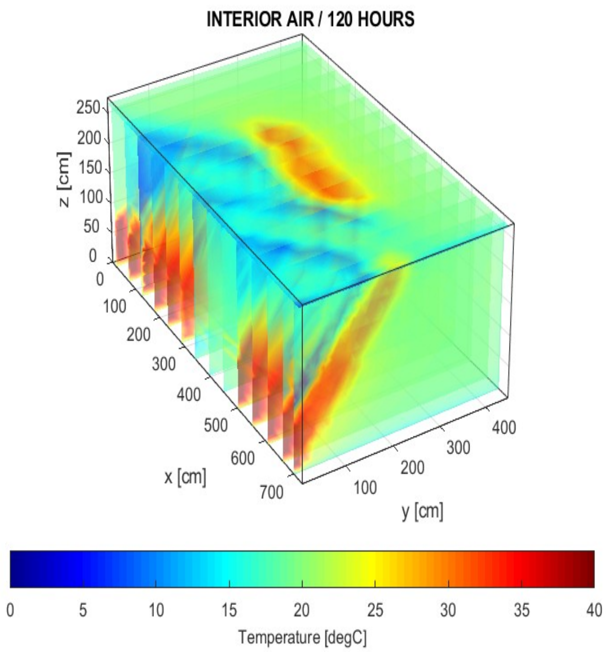

FIGURE 5. The 3D model of air the temperature distribution.

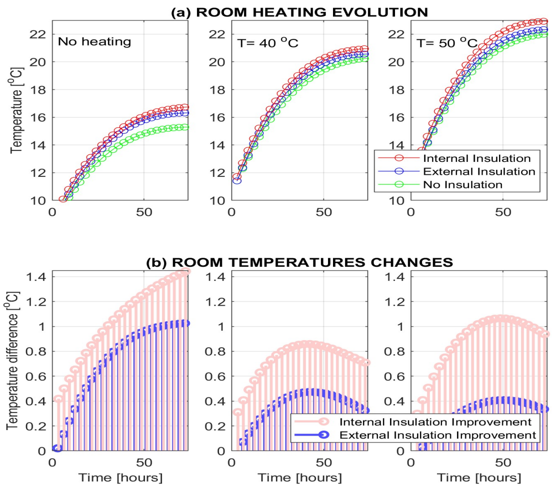

FIGURE 6. Evolution of the air temperature in the heated room when the radiators are off and when the radiators are on with surface temperatures of 40°C and 50°C. a) Air temperature in the center point of the room.
b) Temperature differences between the air in the center point of the thermally insulated room and air in the center point of the uninsulated room.

The output values of the air temperature showed the best efficiency in the model with the thermal insulation placed inside the room. The results are summarized in Table 2. The interior air temperatures were higher in the room with internal thermal insulation than in the room with external thermal insulation or in the non-insulated room. If the radiators were turned off, the time constant was lowest in the uninsulated room.

The evolution over time of the air temperatures during the heating are compared in Fig. 6a. The values indicate the air temperatures of the center of the room. The air temperature differences in a thermally insulated room from the temperature in a non-insulated room at the same time are displayed in Fig. 6b. The highest difference that was achieved by five monitored days was 1.7°C, between the model with thermal insulation inside the room and the model of a non-insulated room when the radiators were turned off and the room was heated only by heat transfer from the neighboring rooms of the house.

The surface temperatures of the walls and ceiling after five days of heating are summarized in Table 3. For comparison, the analyzed wall areas around the critical and opposite corners of the room were divided into segments that corresponded to the vertical distance from the floor $z \in \langle 0, 90 \rangle$ cm

TABLE 3. Results of simulations of the heating of the room. Surface temperatures after five monitored days.

Monitored quantities	Location of the analysed area	CRITICAL CORNER			OPOSITE CORNER		
		Without thermal insulation	Thermal insulation outside the house	Thermal insulation inside the room	Without thermal insulation	Thermal insulation outside the house	Thermal insulation inside the room
HEATING OF THE ROOM: RADIATORS TURNED OFF							
Mean temperature of the surface of the side wall [°C]:	Above window	5.0	4.1	9.9	16.8	17.3	17.5
	Along the window	4.1	7.5	9.7	16.9	17.6	17.9
	Under the window	4.8	11.0	12.6	17.0	17.7	17.9
Mean temperature of the outside wall surface [°C]:	Above window	2.0	4.7	9.7	12.4	13.6	13.8
	Along the window	2.4	5.9	9.4	12.5	13.6	14.7
	Under the window	-0.9	8.6	10.2	13.6	15.3	15.8
Mean temperature of the ceiling surface [°C]:	Ceiling surf. in the corner	6.8	5.8	9.4	15.8	15.9	16.5
HEATING OF THE ROOM: TEMPERATURE OF RADIATORS 40 °C							
Mean temperature of the side wall surface [°C]	Above window	10.3	7.9	15.0	18.7	18.9	19.2
	Along the window	16.3	18.0	21.4	19.6	19.8	20.2
	Under the window	19.5	24.0	25.0	21.8	21.9	22.1
Mean temperature of the outside wall surface [°C]	Above window	5.7	7.9	14.4	13.2	14.3	14.7
	Along the window	10.8	10.7	16.6	13.3	14.4	15.2
	Under the window	16.5	26.9	30.8	19.8	21.6	24.9
Mean temperature of the ceiling surface [°C]	Ceiling surf. in the corner	12.4	9.9	14.1	17.6	17.9	18.1
HEATING OF THE ROOM: TEMPERATURE OF RADIATORS 50 °C							
Mean temperature of the side wall surface [°C]:	Above window	11.9	9.4	16.9	19.4	19.5	19.8
	Along the window	19.7	21.6	25.3	20.6	20.8	21.1
	Under the window	23.6	28.6	29.3	23.9	23.9	24.5
Mean temperature of the outside wall surface [°C]:	Above window	6.8	9.2	15.8	13.5	14.6	15.1
	Along the window	13.3	17.2	19.1	13.6	14.7	15.5
	Under the window	21.7	33.5	38.0	22.1	24.0	28.7
Mean temperature of the ceiling surface [°C]:	Ceiling surf. in the corner	14.2	11.5	16.3	18.2	18.6	18.6

TABLE 4. Results of simulations of the cooling of the room. The time constant, final air temperature, and internal surface temperature after five monitored days.

COOLING OF THE ROOM			
Monitored quantities	**Without thermal insulation**	**Thermal insulation outside the house**	**Thermal insulation inside the room**
Temperature of the air in the center point of the room [°C]:	9.6	9.7	9.6
Mean temperature of the air inside the room [°C]:	5.3	5.7	5.9
Time to achive 75% of the final air temperature [h]:	40.0	40.0	40.5
Time to achive 90% of the final air temperature [h]:	61.0	60.5	61.5
Time constant [h]:	52.0	52.0	52.0

(representing the area below the window), $z \in \langle 90, 245)$ cm (the area along the window), and $z \in \langle 245, 265)$ cm (the area above the window). With regard to the geometric dimensions of the room, the evaluated width (x or y distance from the corresponding corner) is 130 cm. The results for room heating are summarized in Table 3. All mean temperatures in the monitored areas of the analyzed surface show the highest values in the model with thermal insulation inside the room. The results also show higher values of the surface temperature of the walls and ceiling in the opposite corner than in the critical corner of the room.

As shown in Fig. 7a, during the cooling regime, the evolution of the temperature of the uninsulated and thermally insulated room was similar. The maximum air temperature difference in the center of the room was approximately 0.2°C (see Fig. 7b). The air temperature distributions after five days of cooling of the insulated and non-insulated rooms are summarized in Table 4. The time constant and the time required to reach the desired air temperature in the room were almost the same in all cases. As shown in Table 5, the temperature differences between the studied models were mainly visible in the critical wall corner.

TABLE 5. Results of simulations of the cooling of the room. Surface temperatures after five monitored days.

COOLING OF THE ROOM							
Monitored quantities	**Location of the analysed area**	**CRITICAL CORNER**			**OPOSITE CORNER**		
		Without thermal insulation	Thermal insulation outside the house	Thermal insulation inside the room	Without thermal insulation	Thermal insulation outside the house	Thermal insulation inside the room
Mean temperature of the side wall surface [°C]:	Above window	-4.6	-6.9	-3.6	9.5	9.4	9.5
	Along the window	-6.9	-1.8	-5.6	10.1	10.1	10.1
	Under the window	-1.8	5.8	1.4	10.1	10.0	10.1
Mean temperature of the outside wall surface [°C]:	Above window	-7.8	-6.6	-5.5	6.3	7.5	6.9
	Along the window	-8.1	-4.3	-6.4	6.9	8.0	8.5
	Under the window	-8.7	2.4	-5.6	6.7	8.7	8.2
Mean temperature of the ceiling surface [°C]:	Ceiling surf. in the corner	-4.1	-6.6	-6.6	9.7	9.5	9.5

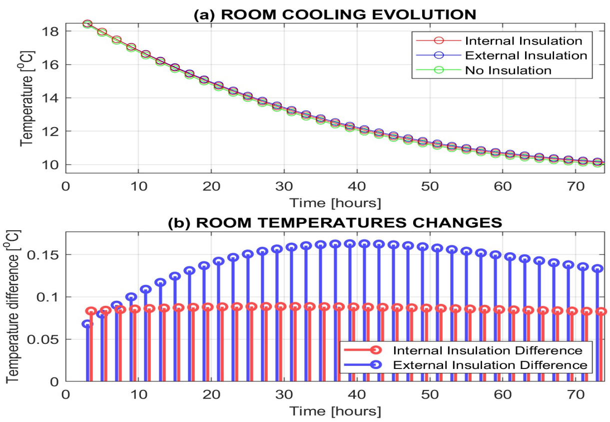

FIGURE 7. Evolution of the air temperature during the cooling of the room. a) Air temperature in the center point of the room. b) Temperature differences between the air in the center point of the thermally insulated room and air in the center point of the uninsulated room.

C. WATER ABSORBENCY IN THE BUILDING STRUCTURE

A simple assessment of the composition of the structure of the building in terms of its absorbency due to the diffusion of water vapor was carried out by calculating the equivalent air layer thickness (see Eq. 5)). The specified thickness of the room's wall layers materials is shown in Table 6. Values of the equivalent air thickness for the tested composition of the structure of a thermally insulated and uninsulated room are summarized in Table 7.

TABLE 6. Thickness and water vapor diffusion resistance factor of the critical and front wall layers.

Wall of the room	Layer	Thickness (δ) [cm]	Water vapor diffusion resistance factor (μ) [-]
Critical wall:	Brick wall	45	9–10
	Thermal insulation	10	20–100
	Exterior facing	1	9–10
Front wall:	Brick wall	25	9–10
	Thermal insulation	10	20–100

TABLE 7. Equivalent air layer thickness of the critical wall and front wall.

Composition of the wall layers		Equivalent air layer thickness (Sd) [m]
Critical wall:	non-insulated	4.14–4.60
	with the external insulation	6.05–14.50
	with the insulation inside the room	6.14–14.60
Front wall:	non-insulate	2.25–2.50
	with the external insulation	4.25–12.50
	with the insulation inside the room	4.25–12.50

For the room's front wall, the values of the equivalent air thickness are the same both in the case of placing the thermal insulation outside the house and inside the room. For the critical wall, the limit values are slightly higher if the thermal insulation is placed inside the room. Assuming the mean values od the diffusion resistance factor, the diffusion resistance thickness of the critical and front walls covered by internal thermal insulation decreases in the direction from the interior of the house to the outdoor. In contrast, the diffusion resistance thickness of the critical and front walls covered by internal thermal insulation increases in the direction from the interior of the house to the outdoor.

D. RISK OF CONDENSATION OF WATER VAPOR IN THE WALLS OF THE CRITICAL CORNER OF THE ROOM

Before installing internal thermal insulation, it is crucial to evaluate the existing wall structure. The wall should be assessed for its current thermal performance and moisture content. This evaluation will help identify any existing moisture-related problems and determine the optimal thickness and material of the insulation to be used. The assessment was carried out by computer simulation in 2D cross-sections with compositions that are similar to the compositions of the side and front walls of the critical corner of the studied room. Insulated and non-insulated walls were compared. The estimated parameters of the wall materials needed for heat and moisture transfer simulations are presented in Table 1

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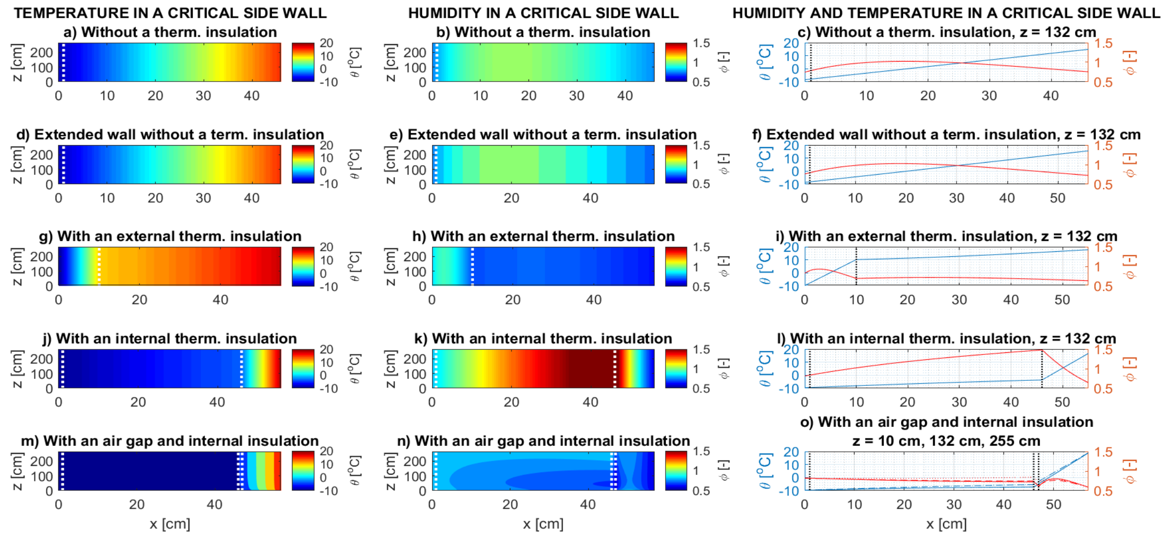

FIGURE 8. Distribution of temperature and humidity in the wall section with a composition similar to that of the side wall of the critical corner of the assessed room. Output data after five days of wall heating display temperature and relative humidity in the wall a), b), c) without thermal insulation; d), e), f) with an extended thickness of 10 cm without thermal insulation; g), h), i) covered by thermal insulation outside the house; j), k), l) covered by thermal insulation in the interior of the house; x distance means the distance in the wall in the direction from the outdoor environment to the interior; m), n), o) with an air gap between the brick wall and the internal thermal insulation; x distance means the distance in the wall in the direction from the outdoor environment to the interior. The white and black dotted lines mark the boundaries of the wall layers.

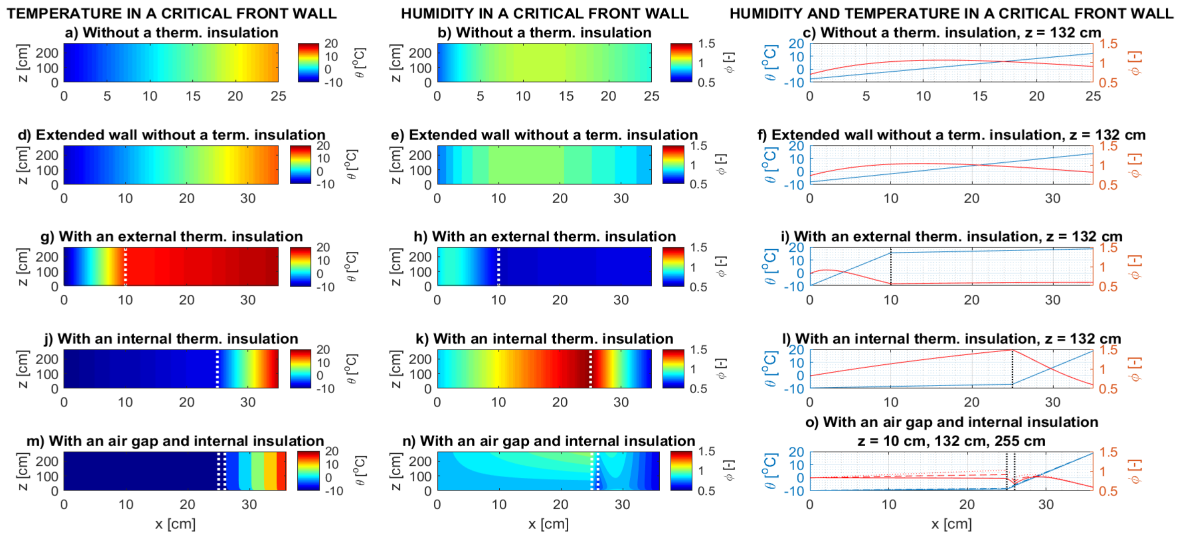

FIGURE 9. Distribution of temperature and humidity in the wall section with a composition similar to that of the front wall of the critical corner of the assessed room. Output data after five days of wall heating display temperature and relative humidity in the wall a), b), c) without thermal insulation; d), e), f) with an extended thickness of 10 cm without thermal insulation; g), h), i) covered by thermal insulation outside the house; j), k), l) covered by thermal insulation in the interior of the house; x distance means the distance in the wall in the direction from the outdoor environment to the interior; m), n), o) with an air gap between the brick wall and the internal thermal insulation; x distance means the distance in the wall in the direction from the outdoor environment to the interior. The white and black dotted lines mark the boundaries of the wall layers.

and Table 6. The initial temperature of the wall was 0°C, and the initial relative humidity of the materials was the same as the relative humidity of the surrounding environment. The heating of the wall was monitored under the conditions:

- Outdoor air temperature -10°C,
- Air temperature inside the room 20°C,
- Relative humidity of the outdoor air 84%,
- Relative humidity of the air inside the room 55%,
- Heat transfer coefficient in the outdoor environment $25\ \mathrm{W/(m^2 \cdot K)}$,
- Heat transfer coefficient in the indoor environment $8\ \mathrm{W/(m^2 \cdot K)}$,
- Outdoor moisture transfer coefficient 2.10^{-8}s/m,
- Indoor moisture transfer coefficient 1.10^{-8}s/m.

The results of the simulations are presented in Fig. 8 and Fig. 9. The output values of temperature and relative humidity of the wall after the monitored five days in the side wall of the critical corner are displayed in Fig. 8. The white and black dotted lines mark the boundaries of the wall layers. The maximum temperarure and the minimum relative humid-

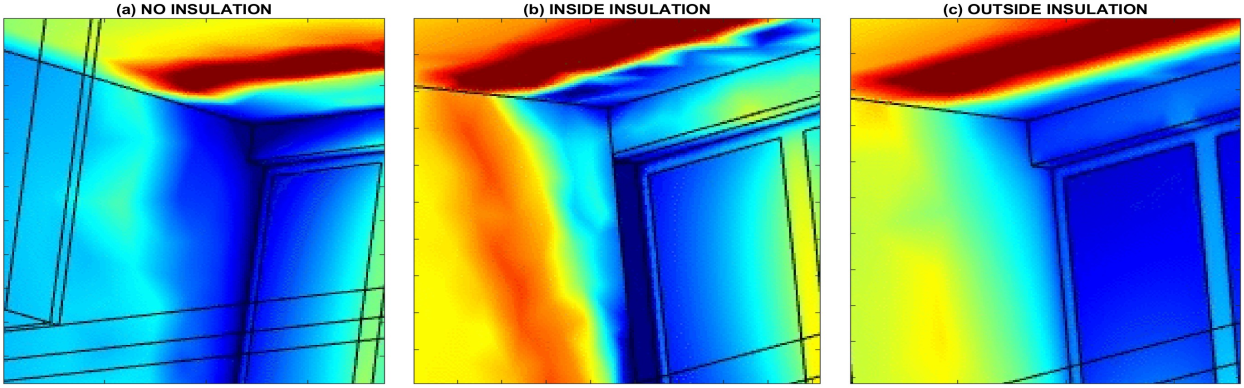

FIGURE 10. Comparison of the effect of the insulation to temperature distribution around the critical room corner presenting the situation (a) without any specific insulation, (b) with inside insulation, and (c) with the outside insulation.

ity were achieved in the wall covered by external thermal insulation (see Figs. 8g,h,i, and Figs. 9g,h,i). In contrast, the wall with internal thermal insulation had the highest relative humidity values and the lowest temperature (see Fig. 8j,k,l). Similar results were also obtained for the front wall of the critical corner of the room, as can be seen in Fig. 9.

The effects of an increase in the thickness of the brick wall and incorporating an air gap between the brick wall and the internal thermal insulation were also tested. The temperature and humidity profiles assuming an increase in the thickness of the side and front critical walls by 10 cm are shown in Fig. 8d,e,f and Fig. 9d,e,f. The results show that this modification did not significantly affect the values of the monitored parameters.

On the other hand, the graphs depicted in Fig. 8m,n,o and Fig. 9m,n,o show that an air gap with a thickness of 1 cm reduced the humidity of the wall. At the same time, there was a slight decrease in the wall's temperature with the air gap. The cold air flows into the gap with a temperature and relative humidity identical to the outdoor environment conditions.

IV. DISCUSSION

The results confirm that thermal insulation of buildings has both some positive effects and risks that need to be considered before installing thermal insulation materials in the construction of a building.

This study focused on testing the effect of the location of expanded polystyrene thermal insulation in the exterior wall of a room in a terraced family house. Computer simulations were carried out for the considered parameters of the structure of the house and boundary conditions corresponding to the winter season of the locality in which the assessed object was located. The results show that, from the point of view of the efficiency of the interior heating of the house, it is more appropriate to place the thermal insulation inside the room. In this case, the interior air temperature is higher than when heating a room with thermal insulation located outside the house or a room without thermal insulation (see Table 2, Fig. 6).

During the heating of the interior, a higher surface temperature of the walls was also detected in the case of internal thermal insulation than external thermal insulation or an uninsulated wall. The results indicate that internal thermal insulation can be a suitable solution for achieving the desired thermal comfort and reducing the risk of mold on the room's walls.

From the point of view of the distribution of moisture in the walls of the critical corner of the room, the results of the simulations showed that external thermal insulation is the most suitable arrangement (see Figs. 8 and 9). However, it was verified that incorporating a gap allows a free air flow between the internal thermal insulation and the brick wall. Under the observed conditions, the relative humidity in the wall containing an air gap decreased by approximately 50% compared to a wall with internal thermal insulation without an air gap.

The analyses carried out by computer simulation tools required many simplifications to define the geometric arrangement and conditions of the studied model. For this reason, the accuracy of the output was verified by an independent experimental comparison using a thermal camera, as described in subsection III-A.

To reduce the complexity of the numerical calculations and burden on the computer's operating memory capacity, plaster and adhesive materials were not included in the assessed room wall models. It was assumed that due to their small thickness and physical properties, they would not significantly affect the diffusion of water vapor through the wall.

In addition to their location, the type and the thickness of the materials of the thermal insulation have a significant influence. In this study, only EPS was tested, which could be a cost-effective alternative for the exterior and interior insulation of the building. In addition, when it is applied at a defined thickness of 10 cm, there would be no significant reduction of the interior space of the building. The main results of the simulations presented in Table 8 include the mean temperatures of the inner surface of the critical side wall, front wall, and air inside the room after five days of heating or cooling. The mean temperature values are calculated from the entire area of the exterior and side critical

TABLE 8. Main results of the heat transfer simulations. Mean temperatures of the inner surface of the critical side wall, front wall, and air inside the room after five days of heating or cooling of the room. The mean temperature values are calculated in the entire area of the exterior and side critical walls of the room.

Monitored quantities	MEAN TEMPERATURE [°C]		
	Without thermal insulation	Insulation outside the house	Insulation inside the room
HEATING OF THE ROOM: RADIATORS TURNED OFF			
Air inside the room	12.7	14.5	14.8
Critical side wall surface	9.0	12.8	13.6
Outside wall surface	6.9	10.9	13.0
HEATING OF THE ROOM: TEMP. OF RADIATORS 40°C			
Air inside the room	19.2	20.0	20.3
Critical side wall surface	17.3	19.8	20.8
Outside wall suface	10.9	14.3	19.8
HEATING OF THE ROOM: TEMP. OF RADIATORS 50°C			
Air inside the room	21.3	22.0	22.2
Critical side wall surface	19.7	22.4	23.2
Outside wall surface	12.2	15.7	22.3
COOLING OF THE ROOM			
Air inside the room	5.3	5.7	5.9
Critical side wall surface	2.0	6.1	3.9
Outside wall surface	0.0	6.5	-0.9

walls of the room. When comparing models with outdoor and indoor insulation, the results show that the location of the insulation does not significantly affect the average indoor air temperature. However, there are noticeable differences in the temperatures of the inner wall surfaces. In heating mode, higher surface temperatures were achieved with internal insulation, while in cooling mode, higher surface temperatures were achieved with external insulation. An influence of the thermal insulation locantion on the surface temperature in the critical corner after five days of the heating mode is shown in Fig. 10. The model with thermal insulation inside the room achieved the best results in the simulation. On the contrary, the lowest surface temperature was found if the walls were not covered by thermal insulation. This confirms that the EPS material can effectively prevent heat loss from the interior of a building to the outdoor.

As shown in Fig. 7a, during cooling the temperature time courses were similar in the uninsulated and thermally insulated room, the maximum air temperature difference in the center of the room was approximately 0.22°C (see Fig. 7b). The results of the temperature distribution comparison after 5 days of cooling of an insulated and non-insulated room are summarized in Table 4. The temperature differences were mainly visible in the temperature of the surface of the critical wall, the exterior wall and the ceiling, which had a higher temperature after 5 monitored days of the room with thermal insulation than the walls of the room without insulation. The time constant and the time required to reach the desired air temperature in the room were almost the same in all cases.

V. CONCLUSION

A numerical assessment of the influence of the location of polystyrene thermal insulation on the thermal comfort of a tested room of a family house was carried out, taking into account the climatic conditions of the monitored location.

Although it was necessary to make many simplifications due to the computational complexity of the process of numerical solving, it can be stated that a thermal analysis software application, such as COMSOL Multiphysics, can be used to model the heat flow and temperature distributions within a room, helping to identify potential thermally critical corners and optimize the design and operation of the space.

The study aimed to evaluate the thermal stability of the tested room and assess the risk of water vapor condensation on the outer wall under specified low outdoor temperature conditions. The study compared the effects of internal and external wall insulation on heat and moisture transfer. The findings indicated that placing the thermal insulation in the interior of the house yielded the best results for heat transfer during the heating regime. However, external wall insulation was found to be the most suitable alternative for moisture transfer.

These results highlight the importance of considering both heat and moisture transfer when selecting the location of the placement of insulation to optimize the overall thermal performance of a building.

Only EPS thermal insulation with the specified thickness of 10 cm was assessed in the present study, but many factors influence heat and moisture transfer in buildings. Therefore, further research is expected to include a more complex analysis of the optimal exterior wall compositions to achieve the required thermal comfort of the house interior under winter and summer conditions.

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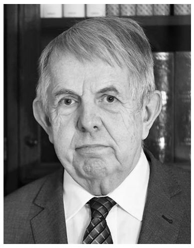

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