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Effects of thermal bridges on the heat demand of residential buildings

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Abstract. This paper presents the influence of the thermal bridges effect on heating demand in residential buildings using numerical simulation. Quantitative evaluation on temperature field is performed by means of linear heat transfer coefficient. Specific details of existing thermal bridges within the building envelope have been identified and selected for analysis. The model simulation was performed using COMSOL Multiphysics software. Thermo-physical properties of the building envelope elements were selected from the software database and the boundary conditions have been setup. Meshing was done by dividing the virtual domain into an optimum number of finite elements. Model validation was done by comparative analysis between the values of the linear thermal transmittance obtained through numerical simulation and the reference values stipulated in C107-3-2005 technical regulation (catalogue of building thermal bridges). Specific solutions for correcting the thermal coupling between different building envelope elements were adopted in order to reduce the linear thermal transmittance up to 23% and the heat flow rate up to 71%. The evaluation of space heating demand shows the impact of correct treatment of thermal bridges on the reduction of energy consumption.

1. Introduction

According to the theory of heat transfer through single-phase materials in direct contact, the combination of several physical environments with different thermo-physical properties generates the appearance of structural geometric perturbations, generating intensification effects of dissipated thermal flows. At the level of the building envelope, these disturbances are called thermal bridges, characterized by a linear thermal transmittance, having direct implications on the stability of their construction and their energy balance [1].

Studies have shown that by disturbing the temperature field and modifying the path of the thermal flux lines, the main negative effect that occurs by concentrating the dissipation of the unit thermal flux in these "thermo-sensitive" areas is the generation of thermal losses through transmission between 8-20% [2].

Another major effect with implications on the hydro-stability of the building and the occupants' health, generated by the lowering of the temperature of the interior boundary surfaces, is the penetration and condensation through the component elements of the construction of water vapour from the interior environment. This phenomenon is responsible for the occurrence and development of dampness and mould with negative effects on the health of the occupants [3], [4].

According to the principles of the "Passive House" standard and the concept of "free design of thermal bridges" developed by PHI (Passive House Institute), to eliminate the negative effects due to



thermal bridges, it is necessary to eliminate or limit the linear thermal transmittance (Ψ) of thermal bridges to the value of $0.01\text{W/m}\cdot\text{K}$ by a "careful treatment" during the design and execution phases of the thermal coupling details between the elements of the building envelope [4].

This paper presents the results obtained from a mathematical modelling and numerical simulation assisted by the specialized software COMSOL MULTIPHYSICS concerning the influence of thermal bridge effect on the transmission heat losses through the façade elements of multifamily residential buildings [5].

2. Materials and methods

2.1. Building description and solutions

The studied building was designed for the purpose of analysing the influence of the effects of the presence of thermal bridges on the thermal coupling between the component elements of the envelope placed on the main façade of the building. The building has a strength structure consisting of reinforced concrete frames and perimeter elements for exterior closure and interior partitioning of brick masonry with thickness of 15 cm. The main façade is shown in figure 1. The calculation surface (S_{op}) of the opaque part (40 elements) of the building façade is 385 m^2 .

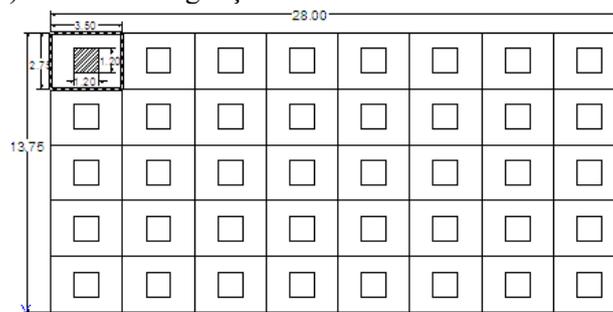


Figure 1. Main façade - 2D general view.

To highlight the behavior of the façade of the building, two solutions were fitted with PVC joinery forty windows. The first adopted case involves equipping with ordinary windows, currently used for the execution of the facades of new or refurbished buildings. The second constructive solution adopted involves equipping the façade with passive energy windows selected from the catalogue of PHI certified components. The total area of calculation (S_{vit}), related to the forty windows of the façade, is $57,6\text{ m}^2$. The geometrical characteristics in plan of the glass elements can be observed in figure 2.

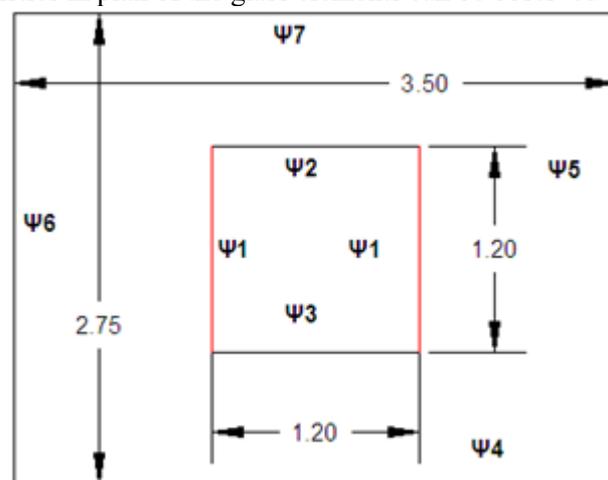


Figure 2. Distribution of the thermal bridges analysed.

In order to increase the energy performance of the analyzed facade, solutions for treating thermal couplings have been adopted in order to reduce thermal losses through the thermal protection of opaque elements with thermal insulation elements of expanded polystyrene and energy efficient montage solutions of the glass component elements of the façade.

For the conformity of the determinations in accordance with the provisions of normative C 107 / 3-2005, the materials' thermo-physical properties of the analysed structure envelope are presented synthetically in table 1 [6].

Table 1. Thermo-physical properties of the building materials.

Material	δ (cm)	c_p (J kg ⁻¹ ·K ⁻¹)	ρ (kg m ⁻³)	λ (W m ⁻¹ ·K ⁻¹)
Cement mortar	2, 3	840	1800	0.93
Brick masonry GVP	25	870	1250	0.5
Window (glaze+frame)	7	1460	1004	0.049
Passive window (glaze+frame)	9	1460	1004	0.045
Cellular polystyrene	10 20	1460	20	0.044

2.2. Domain of simulation

The determination of the calculation / work domain was achieved by choosing a characteristic area of calculation, representing the most vulnerable in terms of energy. This area contains all the elements of the simulation domain, figure 2, located on the corner at the upper level of the building, having the particularity that each surface comes into thermal contact with two physical environments with various thermo-physical properties that are in direct contact with the external environment.

For the purpose of quantitative and qualitative evaluation of the influence of the thermal bridges on the thermal losses through transmission at the facade level, seven characteristic details corresponding to the coupling points between the components of its envelope were considered, resolving seven cases that will be analysed as well [3, 6, 7]:

- Case 1: thermal bridge exterior wall intersection ordinary/passive window - horizontal section, Ψ_1 ;
- Case 2: thermal bridge exterior wall intersection ordinary/passive window top vertical section, Ψ_2 ;
- Case 3: thermal bridge exterior wall intersection ordinary/passive window bottom vertical section, Ψ_3 ;
- Case 4: thermal bridge exterior wall intersection with current floor, Ψ_4 ;
- Case 5: thermal bridge exterior wall intersection with interior wall, Ψ_5 ;
- Case 6: thermal bridge corner out intersection external wall, Ψ_6 ;
- Case 7: thermal bridge attic, Ψ_7 .

For the opaque envelope elements, three different situations were considered: without thermal protection, and with thermal protection with two insulation thickness of 10 cm and 20 cm, for wall and jamb.

In the case of the glazed elements, two types of windows were considered, a first type of window frequently used to equip new residential buildings but also in the case of the rehabilitation of existing ones, and a second type of passive window, mandatory used in passive energy buildings. At the same time, two montage positions were adopted: at the wall thickness, commonly encountered in the case of ordinary windows, and at the middle of the thermal insulation in the case of the mandatory mounting of the passive windows.

2.3. Conditions of uniqueness

The following boundary conditions were defined:

- for temperature: - indoor air temperature, $t_i = 20^\circ\text{C}$;
- outdoor air temperature, $t_e = -15^\circ\text{C}$;

- for heat transfer coefficient:
 - indoor heat transfer coefficient, $\alpha_i = 8 \text{ W/m}^2 \cdot \text{K}$;
 - outdoor heat transfer coefficient $\alpha_e = 24 \text{ W/m}^2 \cdot \text{K}$.

2.4. Conditions of uniqueness

In accordance with the provisions of normative C107 / 3-2005, preliminary geometrical configurations for the constructive elements that make up the details of thermal coupling between facade components were made, for each analysed case [6].

For the construction of the component elements from the case 1, for the coupling detail between the outer wall and the ordinary passive window respectively, the following geometrical features were chosen:

- for the opaque component, a wall with a structure made of brick masonry with dimensions of 25x30cm was considered as reference, having applied a layer of plaster in cement mortar, inside / outside with a thickness of 2 cm, respectively 3 cm, with a total length of 1.2 m, as in figure 3a;
- for the transparent component, it was considered as reference a window with PVC joinery type Brilliant 70, with five rooms, without treatment and insertion of gas with thermo-protective role, with thermal transmittance (U_{win}) of $1.42 \text{ W/m}^2 \cdot \text{K}$, with the length of 0.6 m as in figure 3a.

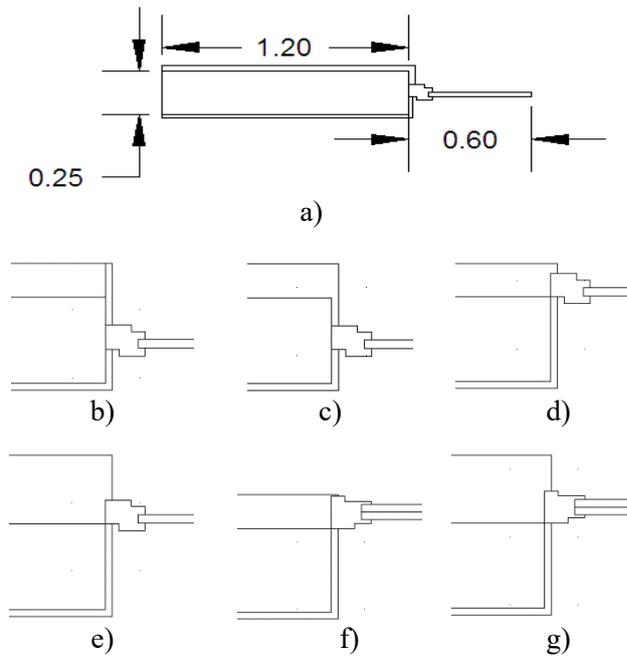


Figure 3. Simulation models, Case 1- (thermal bridge exterior wall intersection with ordinary/passive window - horizontal section).

- a) reference model, (middle montage, without thermal protection)
- b) middle montage, with only wall thermal protection, ($\delta_{wi} = 10 \text{ cm}$)
- c) middle montage, wall and jamb with thermal protection, ($\delta_{wi} = 10 \text{ cm}$, $\delta_{ji} = 2 \text{ cm}$)
- d) montage in insulation, ($\delta_{wi} = 10 \text{ cm}$)
- e) montage in insulation, ($\delta_{wi} = 20 \text{ cm}$)
- f) passive window, montage in insulation, ($\delta_{wi} = 10 \text{ cm}$)
- g) passive window, montage in insulation, ($\delta_{wi} = 20 \text{ cm}$)

Starting from the reference structure, various thermo-protection measures of the opaque element of different dimensions were applied and two montage variants were adopted for the windows: in the middle of the gap intended for it, as well as next to the insulation, in horizontal section, as presented in figure 3b, c, d and e.

Also, to highlight the energy efficiency of passive certified energy components, the basic window was replaced with a window for passive houses, type Geneo HST, with three sheets of glass, thermal treatment of glass, selected from the passive component catalog of the PHI, with thermal transmittance (U_{win}) of $0.79 \text{ W/m}^2 \cdot \text{K}$ and montage next to the insulation, as in figure 3f and g.

Similarly, the other cases of thermal bridges representing the top and bottom vertical sections of the coupling details between the external wall and the standard or passive window were analysed and the obtained results were interpreted.

Also, for the cases that highlight the thermal bridges, simulation of the direct coupling between the opaque components of the building envelope were made, adopting appropriate correction solutions in order to reduce their influence on the heat losses through transmission [8].

2.5. Nodal network generation

In order to evaluate the behaviour of the analysed structures, modelling and numerical simulation of the heat transfer through the specific simulation field for each detail of coupling between the component elements of the facade was realized with the COMSOL MULTYPHISICS commercial software.

This virtual environment, organized on interconnected working modules, provides tools for modelling physical environments and simulating physical processes, easy-to-use interfaces, algorithms for efficiency, and offers the possibility to control the simulation process based on the links between partial differential equations, in order to assess and quantify the analysed process parameters, allowing after the data processing the quantification of the parameters and establishing the suitable solution [9].

In order to analysis the steady-state regime of the processes of heat transfer, from the available module package, the General Heat Transfer module was chosen to work with.

For the modelling and simulation of the heat transfer through the simulation domain, the conduction heat transfer module has been selected which uses the well-known Fourier's law of heat conduction for heat flux calculation (equation 1):

$$q = -k \cdot A \cdot dT/dx \quad (1)$$

where q is the heat-transfer rate in W, A the cross-sectional area in m^2 , k the thermal conductivity of the material in $W/(m \cdot K)$ and dT/dx the temperature gradient in K/m .

After the simulation geometry is loaded from AutoCAD, the first preliminary steps for launching the computer simulation consists of its conversion into a solid environment, setting the data specific to the sub-domains represented by the component layers of the analysed structure and the boundary conditions for the delimiting boundaries of the simulation domain [1].

For the simulation domain discrepancy, the finite element method was adopted, characterized by the fact that a certain virtual domain is subdivided into a number of finite elements, sub-domains with variable dimensions and shapes, which are interconnected by discrete number of nodes [8].

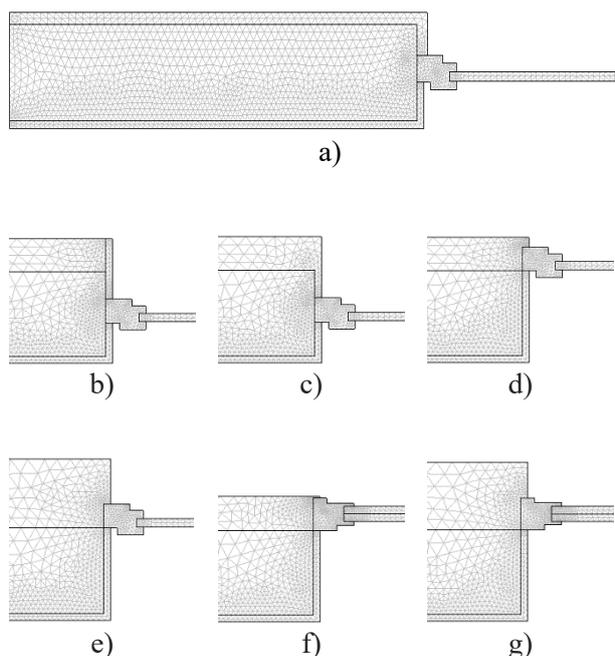


Figure 4. Nodal network Case 1- (thermal bridge exterior wall intersection with ordinary/passive window -horizontal section).

- a) reference model, (middle montage, without thermal protection, 3280 elements);
- b) middle montage, with only wall thermal protection, ($\delta_{wi} = 10\text{cm}$, 2924 elements);
- c) middle montage, wall and jamb with thermal protection, ($\delta_{wi} = 10\text{cm}$, $\delta_{ji} = 2\text{cm}$, 2840 elements);
- d) montage in insulation, ($\delta_{wi} = 10\text{cm}$, 2964 elements);
- e) montage in insulation, ($\delta_{wi} = 20\text{cm}$, 3020 elements);
- f) passive window, ($\delta_{wi} = 10\text{cm}$, 3616 elements);
- g) passive window, montage in insulation, ($\delta_{wi} = 20\text{cm}$, 3448 elements).

Then, the following simplifying working hypotheses were established: stationary regime, constant boundary temperature, no heat transfer through radiation, no internal heat sources.

The method of dividing the simulation domain consists in the unequal distribution of the finite elements of the nodal network with linear tetrahedral form, with higher density of elements near the delimiting borders of the simulation domain.

Figure 4 shows the profiles of the nodal networks of the simulation domains for Case 1.

2.6. Heat losses transmission

For the quantitative evaluation of the heat losses by transmission through the envelope element of the building, the linear thermal transmission specific to the details of linear thermal bridges, based on the transferred thermal flux, quantified and provided by the Comsol Multiphysics application, was determined in advance.

In order to determine the linear thermal transmittance, characterizing the linear thermal bridge the calculation relation (2) was used, between the thermal flux estimated following the simulation process and the thermal flux dissipated through the current field area of the contraction elements of the building between which the thermal bridge is established [7, 10, 11].

After the value estimation of the total thermal fluxes transferred through the analysed simulation domain, a correction of these values was made for the length unit of the domain boundaries. For the determination of the physical quantities that take into account the heat losses through transmission, the average value was used.

$$\Psi = (\Phi_{2D,med, Comsol} - \Phi_{1D,calc})/\Delta t \quad (2)$$

in which $\Phi_{1D,calc} = \Sigma(U_i \cdot l_i)\Delta t$

$$\Psi = (\Phi_{2D,med,Comsol}/\Delta t) - \Sigma(U_i \cdot l_i) \quad (3)$$

where Ψ is the linear thermal transmittance in $W/m \cdot K$, $\Phi_{2D,med,Comsol}$ the average adjusted thermal flow evaluated by the Comsol Multiphysics application in W/m , U_i the thermal transmittance of component i of the building envelope in $W/m^2 \cdot K$, l_i the characteristic length of the element "i" in m and Δt the temperature difference between indoor and outdoor in K.

For the validation of the working study, the values obtained for the linear thermal transmittance, based on the data obtained from the simulation and the calculation relationships, were compared with the reference ones from the catalogue with standard thermal bridges specific to the buildings, annex K of the order 1950. In all cases, the relative error was found below 5%.

The determination of heat losses by transmission, specific for a characteristic element of the building facade, analysed for cases 1, was made using the following equation:

$$Q_{tr} = [U_{wall} \cdot (A_{wall} - A_{win}) + U_{fr} \cdot A_{fr} + U_{gl} \cdot A_{gl} + 2\Psi_l \cdot l_{win}] \cdot \Delta t \quad (4)$$

where Q_{tr} is heat losses by transmission in W, Ψ linear thermal transmittance in $W/m \cdot K$, U_{wall} thermal transmittance of wall in $W/m^2 \cdot K$, U_{fr} thermal transmittance of frame in W/m^2 , U_{gl} thermal transmittance of glass in $W/m^2 \cdot K$, A_{wall} length of wall in m, A_{fr} length of frame in m, A_{gl} width of the glass, m, l_{win} length of the window in m and Δt temperature difference between indoor and outdoor in K.

3. Results and discussions

Through computer simulation of heat transfer for the simulation of coupling details, the following aspects were analysed:

- the quantitative distribution of the temperatures field;
- the quantitative distribution of the unitary heat flux transferred through the surface unit.

The qualitative distribution of the temperature field through the surface unit, for the case of the coupling between the external wall and the standard window, in a horizontal section, is shown in figure 5a, b, c, d, e. For the coupling details in which the passive window was used, the qualitative distribution of the temperature field is shown in figure 5f, g.

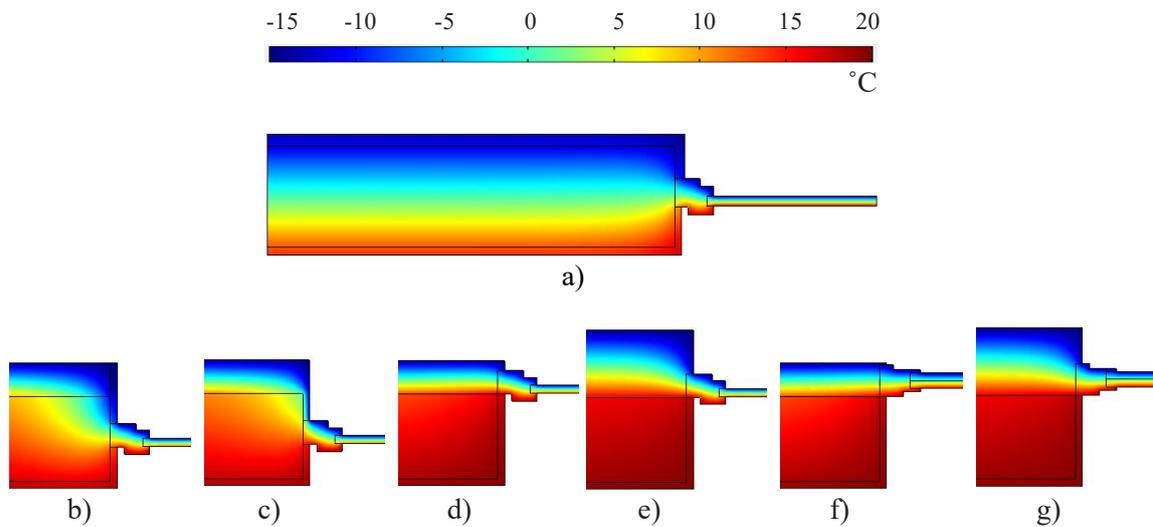


Figure 5. Temperature field distribution, Case 1- (thermal bridge exterior wall intersection with ordinary/passive window- horizontal section).

In the case of the details coupling in the case 1a, b, c, d, which uses the standard window as can be seen in the reference case, when the wall unprotected field distribution of the temperature is very varied, by applying the measures of thermal protection the coupling, a thermal stability of the component elements is obtained.

A thermally efficient correction measure proves to be in the situation where the window is mounted in the field of insulation of the outer wall.

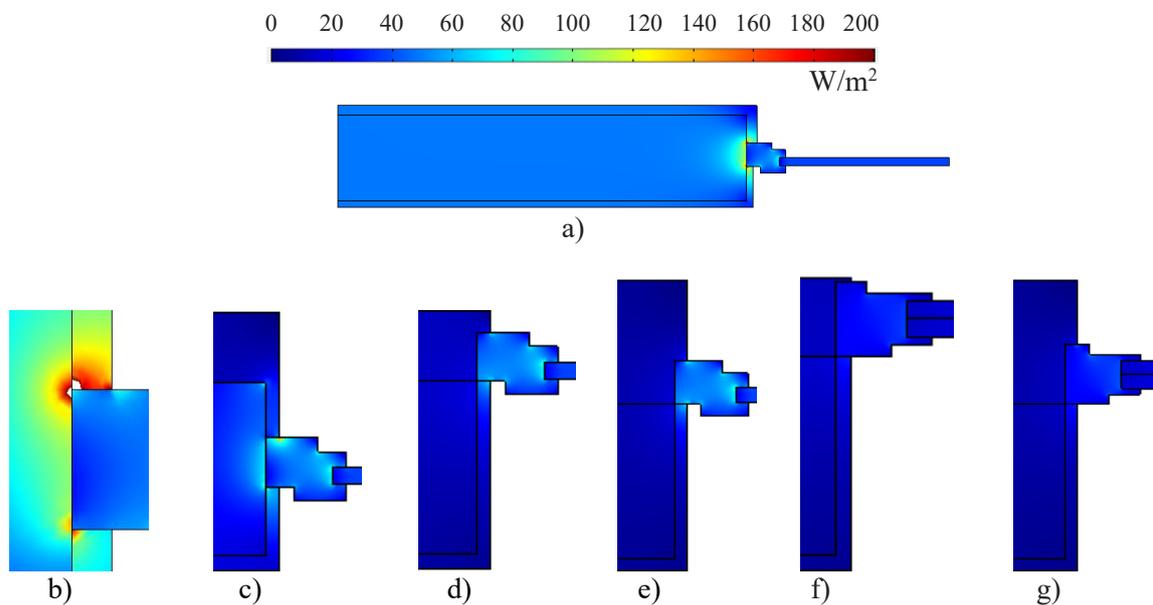


Figure 6. Total thermal flow Case 1- (thermal bridge exterior wall intersection with ordinary/passive window- horizontal section):

- a) - reference model (middle montage, $\Phi_{it}=233\text{W/m}^2$); b) - middle montage ($\delta_{wi}=10\text{cm}$, $\Phi_{it}=326\text{W/m}^2$);
 c) - middle montage ($\delta_{wi}=10\text{cm}$, $\delta_{ji}=2\text{cm}$, $\Phi_{it}=154\text{W/m}^2$); d) - montage in insulation ($\delta_{wi}=10\text{cm}$, $\Phi_{it}=101\text{W/m}^2$);
 e) - montage in insulation, ($\delta_{wi}=20\text{cm}$, $\Phi_{it}=96\text{W/m}^2$); f) - passive window ($\delta_{wi}=10\text{cm}$, $\Phi_{it}=50\text{W/m}^2$);
 g) - passive window ($\delta_{wi}=20\text{cm}$, $\Phi_{it}=47\text{W/m}^2$).

The best technical solution design and execution efficient thermal coupling, which can be adopted and offers very good thermal stability is when using a passive energy efficient window mounted exclusively in the passive field of external wall thermal protection.

The second aspect of the qualitative evaluation of the heat transfer through the components of the building envelope is materialized by the distribution of the heat flow transferred through the surface unit, specific to the details of case 1, presented in figure 6a, b, c, d, e, f, g.

From the analysis of the distribution of the total thermal flux through the simulation domains corresponding to case 1, it appears that, in the reference variant, the thermal flux transferred through the building elements of the building undergoes changes of intensity in the area where the thermal bridge manifests up to the reference value of 233 W/m².

Applying the thermal protection measures to the opaque element, the dissipation of the thermal flux through the thermal bridge is intensified, increasing by 40% from the reference value to 326 W/m². If corrective measures are adopted by insulating the thermal bridge the dissipated thermal flux is reduced by 34% (up to 154 W/m²) compared to the reference situation, and by changing the position of the window in the field of wall insulation up to 59% (96 W/m²). If the specific conditions for passive houses are imposed by using the energy efficient windows installed in the insulation field, the unit thermal flux dissipated through the thermal bridge is reduced up to 80%, reaching the value of 47 W/m².

The results of the determinations of the physical parameters based on the calculation formulas presented above, which characterize the behaviour of the investigated details, applying certain strategies for limiting the effects of the thermal bridges with exterior wall intersection for ordinary and passive window, as well as the relative errors, ε , are summarized in table 2.

Table 2. Physical parameters determination Case 1

Case	$\Phi_{2D,med}$ (W m ⁻¹)	ε_{ϕ_l} (%)	Ψ_l (W m ⁻¹)	ε_{ψ_l} (%)	Q_{tr} (W)	$\varepsilon_{Q_{tr}}$ (%)
1a	92,49	0	0,279	0	481,9	0
1b	50,88	-45,0	0,350	25,7	187,0	-61,2
1c	46,31	-49,9	0,219	-21,3	176,0	-63,5
1d	42,40	-54,2	0,108	-61,3	166,6	-65,4
1e	35,51	-61,6	0,087	-68,8	122,9	-74,5
1f	27,96	-69,8	0,056	-80,0	131,5	-72,7
1g	20,69	-77,6	0,024	-91,3	86,8	-82,0

Analysing the parameters summarized in Table 2 the following observations may be made:

- the value of the thermal flux in the two dimensional field transferred through the simulation domain estimated by the Comsol software decreases by 77% from the reference value;
- the linear thermal conductivity that characterizes the thermal bridge that generates the flow of heat through it increases with the thermal corrections brought to the opaque element, as in case b. With the adoption of strategies to reduce the dissipative effect of the thermal flux, there is a gradual decrease in the value of linear thermal conductivity by 91% compared to the reference case, very close to the upper limit of the passive domain of 0.01 W/m·K.
- the heat losses through transmission through an envelope element of the building generated by the presence of the thermal bridges specific to the analyzed case 1 are substantially reduced compared to the reference case by up to 82%, which leads to a considerable reduction of the heat requirement to cover these losses.

4. Conclusions

Following the modelling and simulation of the heat transfer through the specific simulation domains of the analysed case, the following conclusions are drawn:

- the temperature distribution in the structure of the construction elements is directly influenced by the presence of linear thermal bridges due to the structural perturbations that occur at the contact between the construction materials with different thermal properties;
- the technical solutions for the correction of the thermal couplings between the construction elements through thermo-protection measures and the use of energy efficient components for limiting the dissipative effects of the transferred thermal flow lead to substantial reductions in the heat loss through transmission at the building envelope level;
- in addition to the energy efficiency of the building by reducing or eliminating the effects of thermal bridges, the risk of degradation of the structural elements or perimeter of the building is eliminated, and a healthy environment and a high inside thermal comfort for the occupants are achieved.

Acknowledgments

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