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Assessment of thermal performance and surface moisture risk for a rear-ventilated cladding system for façade renovation

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Assessment of thermal performance and surface moisture risk for a rear-ventilated cladding system for façade renovation

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Abstract. Ventilated façade systems, incorporating thermal insulation behind a rear-ventilated cladding, constitute a popular renovation solution in warm European climates. For compliance with building regulations, their energy efficiency is usually obtained through simple one-dimensional desktop calculations, which do not consider the impact of the support elements of the cladding penetrating the thermal insulation. This study assesses a ventilated façade system anchored over a solid concrete wall with adjustable stainless steel brackets. One-dimensional calculations are compared against three-dimensional numerical thermal modelling, evaluating the effect of insulation thickness (40–100 mm) and potential gaps in the insulation around anchors. Results indicate low risk of condensation and mould growth over internal surfaces. The additional heat flow induced by stainless steel anchors, which is not considered by simplified calculations, appears lower than for aluminium-based systems but can become significant as insulation levels increase. Ensuring the continuity of insulation around anchors is critical for keeping this additional heat flow at reasonable levels (8–13%). If gaps in the insulation are present around anchors, the additional heat flow increases substantially (25–70%) and pushes effective U-values above 0.4 W/m²K, thus resulting in unforeseen energy consumption and non-compliance with regulatory requirements in many European locations.

1. Introduction

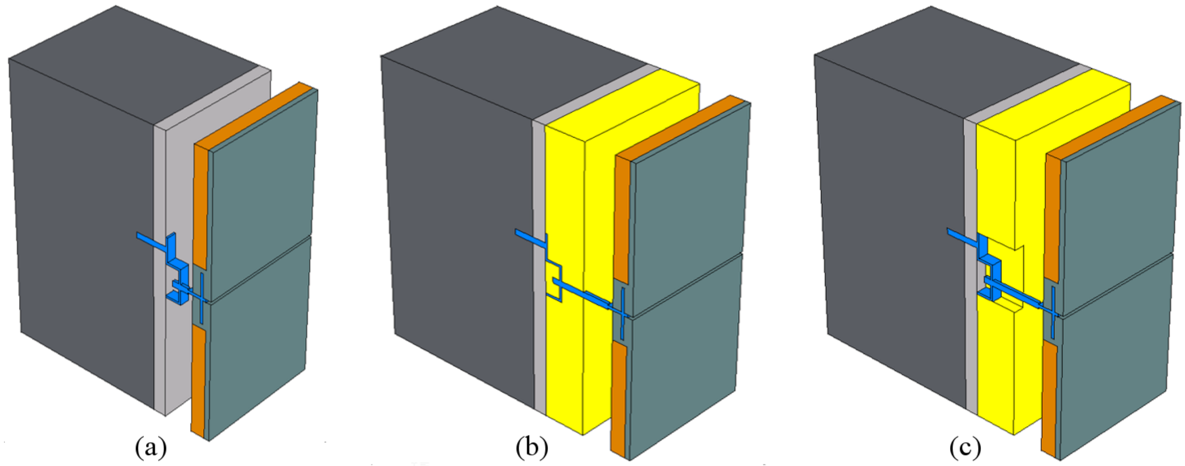
Ventilated façade systems are a well-suited solution for the energy-focused renovation of external walls in Southern European climates [1][2]. Such systems incorporate a rear-ventilated cladding as external finish, with thermal insulation placed against the external surface of the original wall. Their main distinguishing feature is the air cavity that separates the cladding from the insulation, which is drained and ventilated, thus protecting the insulation from driving rain while allowing evaporation of any built-in or diffusion-driven moisture. Further thermal benefits are achieved in warm climates during the cooling season, as the cladding prevents most heat gains from solar radiation, and the stack effect within the ventilated cavity aids the dissipation of heat [3][4].

Regulatory requirements for thermal performance are usually set in the form of a maximum thermal transmittance (*U*-value) [5]. Such values are often calculated for compliance with regulations through simplified one-dimensional calculation. However, as the cladding is anchored to the existing structure of the building, the fixing elements necessarily puncture the thermal insulation layer and thus constitute three-dimensional thermal bridges. Despite consideration of thermal bridges is widely acknowledged as necessary, their magnitude is rarely quantified or calculated in practice. Furthermore, the use of default values tends to underestimate the extent of heat flow [6].

This report assesses the renovation of an external wall with a ventilated façade system developed within the framework of the InnoWEE project. It has a twofold purpose of determining the heat flow through the anchoring elements for a more accurate thermal characterization of the full system and assessing the potential for hygrothermal risk (surface condensation or mould growth) over internal surfaces, using numerical thermal modelling methods. A conventional anchoring system comprised of a subframe made of vertical profiles and L-shaped aluminium brackets was assessed on an earlier study [6]. The present paper assesses the renovation of an uninsulated external wall with a ventilated façade system which is fully supported through adjustable brackets. Section 2 provides a more thorough description of the studied assembly and fastening system.

2. Case study

A reinforced concrete wall, externally finished with a lime render, has been adopted as a case study for an existing wall to be renovated. It is intended to represent a conservative case, as it contains neither thermal insulation nor any cavity. The assessed ventilated façade system is applied as a retrofit solution over this original wall. It incorporates thermal insulation placed against the external surface of the existing wall, a ventilated cavity, and an external cladding developed within the InnoWEE project, made of high-density geopolymer (HDG) panels incorporating wood geopolymer inserts, with overall dimensions of 0.6 m × 0.6 m. Each of these panels is supported at four points (two at the top, two at the bottom) by stainless steel adjustable body anchors (figure 1) comprising a bracket, rivet nut, spade bolt with locking nut and washer. The material properties of the original and renovated assemblies are indicated in tables 1 and 2.



(a) (b) (c)

Figure 1. Assessed ventilated façade system: (a) no insulation, (b) insulation with no gap around anchor, (c) insulation with air gap in the projection of the anchor.

Both the original and renovated façade have been assessed. In the latter, in order to determine the impact of insulation thickness, different cases have been considered: one with no thermal insulation (figure 1a), and four different thicknesses of insulation (40/60/80/100 mm) with a thermal conductivity of 0.038 W/mK. For the renovation cases incorporating thermal insulation, two scenarios have been assessed: an ideal case where the insulation wraps the steel anchor with no gaps (figure 1b), and a more common scenario with a gap in the insulation over the perpendicular projection of the anchor (figure 1c).

3. Methods

A series of thermal analyses have been performed combining simplified calculations and numerical modelling. The energy performance has been measured by the thermal transmittance, while the temperature factor has been used as a metric for the risk of surface condensation of mould growth. These are further detailed below.

The thermal transmittance (commonly known as U-value) is frequently used in building regulations and construction practice as a measure for the thermal performance of building envelope components. Equation (1) assumes that the heat flow across the building component is steady-state and one-dimensional.

$$\phi = U \cdot A \cdot \Delta T \tag{1}$$

where: ϕ is the heat flow rate across the component [W]
U is the thermal transmittance of the component [W/m²K]
A is the surface area of the component [m²]
ΔT is the difference of temperature at both boundaries [K or °C]

The temperature factor has been used as a metric for evaluating the risk of condensation or mould growth over the internal surface of a building component [7]. It is calculated as per equation (2), which also assumes a steady-state condition. The temperature factor can be understood as a dimensionless value that is a property of the building component, unaffected by boundary conditions. It indicates where the internal surface temperature sits within a scale ranging from 0 (external boundary temperature) to 1 (internal boundary temperature).

$$f_{R\mathrm{si}} = (T_{\mathrm{si}} - T_{\mathrm{e}}) \;/\; (T_{\mathrm{i}} - T_{\mathrm{e}}) \tag{2}$$

where: $f_{R\mathrm{si}}$ is the temperature factor of the component
T_{si} is the internal surface temperature [K or °C]
T_{i} is the internal boundary temperature [K or °C]
T_{e} is the external boundary temperature [K or °C]

3.1. One-dimensional calculation

As a first step, a simplified one-dimensional calculation has been performed. This method considers all layers of the building component as plane elements and does not take account of thermal bridges (such as anchoring elements) or other discontinuities [8]. As shown by equation (3), the U-value can be calculated as the inverse of the total thermal resistance, that is the sum of the thermal resistances of all layers of the assembly, including internal and external surface resistances.

$$U = (R_{\mathrm{si}} + \textstyle\sum_i R_i + R_{\mathrm{se}})^{-1} \tag{3}$$

where: U is the thermal transmittance of the component [W/m²K]
R_{si} is the internal surface resistance [m²K/W]
R_i is the thermal resistance of each layer i of the assembly [m²K/W]
R_{se} is the external surface resistance [m²K/W]

The temperature factor can be calculated as per equation (4), which is also based on one-dimensional heat flow [7].

$$f_{R\mathrm{si}} = 1 - R_{\mathrm{si}} \cdot U \tag{4}$$

where: $f_{R\mathrm{si}}$ is the temperature factor
R_{si} is the internal surface resistance [m²K/W]
U is the thermal transmittance of the component [W/m²K]

3.2. Three-dimensional thermal modelling

The impact of anchoring elements on the thermal performance of a wall can be considered by modifying equation (1) to include an additional term for point thermal bridges, as shown in equation (5).

$$\phi = (U \cdot A + \chi \cdot n) \cdot \Delta T \quad (5)$$

where: ϕ is the heat flow rate across the component [W]
U is the thermal transmittance of the component [W/m²K]
A is the surface area of the component [m²]
χ is the point thermal transmittance of an anchor [W/K]
n is the number of anchors of the component
ΔT is the difference of temperature at both boundaries [K or °C]

In order to determine the point thermal transmittance of the anchors, for each scenario assessed, a three-dimensional thermal model of an anchor has been built and solved numerically using software TRISCO 13.0w. In such models, the anchor is split through its vertical symmetry axis, thus including half of the anchor and a flanking area of wall. The models (figure 2) extend 1 metre beyond the anchoring point in the horizontal direction, and 1 metre above and below it in the vertical direction [9].

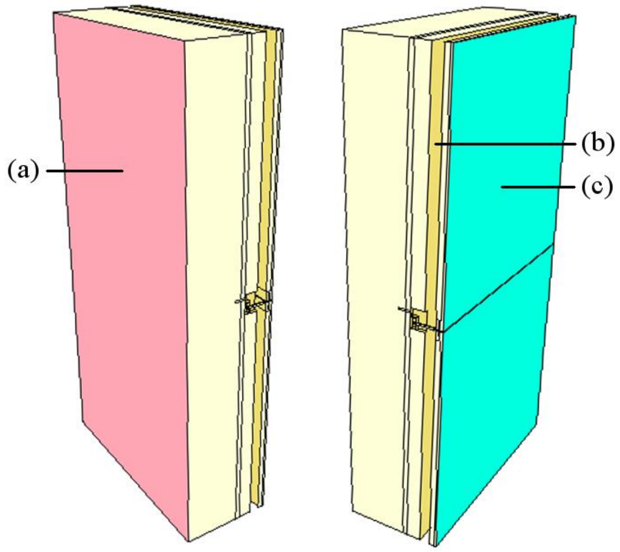


Figure 2. Internal and external view of three-dimensional thermal model of assessed ventilated façade system. Boundary conditions: (a) interior, (b) ventilated cavity, (c) exterior.

By definition, the point thermal transmittance measures the multi-dimensional heat flow, that is the heat flow additional to the one-dimensional heat flow measured by the *U*-value. Equation (5) can be used to describe the heat flow through each numerical model, where *U* is the one-dimensional thermal transmittance calculated through equation (3), ΔT and *A* are inputs to the model, and ϕ is the output from the numerical model. By using n=1/2 (since only one half of the anchor is included in the model) the point thermal transmittance χ can be obtained.

A drawback of equation (5) is that all parameters described above need to be specified for determining the one-dimensional thermal transmittance and the multi-dimensional point thermal transmittance. It is convenient to incorporate the impact of the anchors into an equivalent *U*-value, so that the simpler equation (1) can be used. Such an equivalent *U*-value has been determined as per equation (6), where the first term of the equation describes the one-dimensional heat flow obtained by calculation and the second term captures the three-dimensional heat flow obtained through the numerical model.

$$U_{\mathrm{eq}} = U + \chi \cdot d \quad (6)$$

where: U_{eq} is the equivalent thermal transmittance of the component [W/m²K]
U is the 1D thermal transmittance of the component [W/m²K]
χ is the point thermal transmittance of an anchor [W/K]
d is the density of anchors per area [/m²]

Finally, the temperature factor has been directly calculated from the numerical model using equation (2), with boundary temperatures taken as the model inputs and the internal surface temperature corresponding to the coldest point in the vicinity of the anchor as per model outputs.

3.3. Boundary temperatures and surface resistances

For the existing wall, an external surface resistance of 0.04 m²K/W has been adopted for all calculations [7][8]. The air cavity of the retrofitted wall is intended to be ventilated, and so it has been considered as a well-ventilated air layer for the purpose of thermal performance calculations. Given the normalised procedure for thermal calculations [8], the thermal resistance of the air layer and the cladding have been discarded, and an increased surface resistance of 0.13 m²K/W has been used for the surface of the wall facing the well-ventilated cavity.

Internal surface resistances to be adopted depend on the purpose of the calculation. For heat flow calculations (planar and point thermal transmittances) using equations (1), (3), (5) and (6), a surface resistance of 0.13 m²K/W has been taken, corresponding to horizontal heat flow [8]. However, for assessing moisture risk (temperature factor) using equations (2) and (4), an increased internal surface resistance of 0.25 m²K/W has been adopted [7]. This is intended to represent the conditions at vulnerable locations such as corners, curtains, furniture or suspended ceilings.

Surface resistances used in three-dimensional models are consistent with those used in one-dimensional calculations. Therefore, two numerical models (with differing internal surface resistance) have been built for each scenario: one for the purposes of U-value calculation, and another one for obtaining the temperature factor.

Boundary temperatures of 20 °C (external) and 0 °C (internal) have been adopted for the numerical models; however, the steady-state metrics obtained through the models (U-value and temperature factor) are independent of these input parameters.

4. Results

4.1. One-dimensional calculation

A one-dimensional calculation of the thermal performance of the original wall, calculated using equation (3), is presented in table 1. The thermal transmittance of the original façade is calculated at $U = 2.79$ W/m²K.

Table 1. Thermal performance of existing façade obtained through one-dimensional calculation.

	Thickness [m]	Th. conductivity [W/mK]	Th. resistance R [m²K/W]	Reciprocal of R [a, b, c] [W/m²K]
Internal surface resistance	-	-	0.13	7.69 [a]
Monolith reinforced concrete	0.250	1.51	0.166	6.04 [b]
Lime render	0.020	0.87	0.023	43.5 [b]
External surface resistance	-	-	0.04	25 [a]
Total	0.270	-	0.359	2.79 [c]

[a] Heat transfer coefficient (h).
[b] Thermal conductance (Λ).
[c] Thermal transmittance (U).

An analogous calculation of the thermal performance of the retrofitted wall is presented in table 2. The thermal transmittance with no insulation is calculated at $U = 2.23$ W/m²K. When thermal insulation is incorporated (assuming a thermal conductivity of $\lambda = 0.038$ W/mK), the U-value is a function of insulation thickness, ranging from 0.67 W/m²K ($e = 40$ mm) to 0.32 ($e = 100$ mm) for the cases assessed.

Table 2. Thermal performance of retrofitted façade obtained through one-dimensional calculation, as a function of the thickness (*e*) and thermal conductivity (λ) of the thermal insulation.

	Thickness [m]	Th. conductivity [W/mK]	Th. resistance *R* [m²K/W]	Reciprocal of *R* [a, b, c] [W/m²K]
Internal surface resistance	-	-	0.13	7.69 [a]
Monolith reinforced concrete	0.250	1.51	0.166	6.04 [b]
Lime render	0.020	0.87	0.023	43.5 [b]
Thermal insulation	e	λ	e / λ	λ / e [b]
Cavity surface resistance	-	-	0.13	7.69 [a]
Ventilated cavity	0.045	-	-	-
External cladding	0.030	-	-	-
Total	$0.345 + e$	-	$0.449 + e / \lambda$	$(0.449 + e / \lambda)^{-1}$ [c]

[a] Heat transfer coefficient (h).
[b] Thermal conductance (Λ).
[c] Thermal transmittance (U).

Table 3 presents the one-dimensional calculations for the temperature factor of the existing and renovated wall. The U-values listed are purely instrumental and should only be used for temperature factor calculations under simplified equation (4).

Table 3. Temperature factor, obtained through one-dimensional calculation, for façade in existing condition and retrofitted with assessed ventilated façade system (thermal insulation of $\lambda = 0.038$ W/mK).

	R_{si} [m²K/W]	U [W/m²K]	f_{Rsi}
Existing façade	0.25	2.090	0.48
Retrofitted façade with no insulation	0.25	1.759	0.56
Retrofitted façade with 40 mm insulation	0.25	0.617	0.84
Retrofitted façade with 60 mm insulation	0.25	0.466	0.88
Retrofitted façade with 80 mm insulation	0.25	0.374	0.91
Retrofitted façade with 100 mm insulation	0.25	0.312	0.92

4.2. Three-dimensional thermal modelling

Results from thermal modelling are presented in table 4. For comparison purposes, results from one-dimensional calculations (obtained through the procedure described in section 4.1) are shown in the first section of the table.

With regard to three-dimensional calculations, the heat flow and internal surface temperature of the model are outputs from the modelling software, and they relate to the thermal model depicted in figure 2. The point thermal transmittance of fixings for each case has been obtained through equation (5) following the method described in section 3.2. Subsequently, equation (6) has been applied to obtain an equivalent U-value for each scenario. The density of anchors per area (5.56/m²) has been obtained by dividing the number of anchors per cladding panel (4/2) by the overall dimensions of each panel (0.6 m × 0.6 m). Finally, the temperature factor at the coldest point near the anchor for each case has been calculated through equation (2) as described in the last paragraph of section 3.2.

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Table 4. *U*-value and temperature factors, excluding and including the impact of fixings, for façade retrofitted with the assessed ventilated façade system.

Insulation thickness		[mm]	0	40	60	80	100
(a) One-dimensional calculation							
U	U-value disregarding fixings	[W/m²K]	2.231	0.666	0.493	0.392	0.325
f_{Rsi}	Temperature factor disregarding fixings		0.560	0.846	0.884	0.907	0.922
(b) Three-dimensional model, with insulation tight around anchor							
ϕ	Heat flow of model	[W]	89.26	26.75	19.82	15.75	13.07
χ	Point thermal transmittance of fixings	[W/K]	0.003	0.010	0.009	0.009	0.008
U_{eq}	U-value including impact of fixings	[W/m²K]	2.247	0.722	0.543	0.441	0.369
T_{si}	Internal surface temperature of model	[°C]	11.17	16.84	17.60	18.07	18.38
f_{Rsi}	Temperature factor considering fixings		0.559	0.842	0.880	0.904	0.919
(c) Three-dimensional model, with insulation removed in the projection of the anchor							
ϕ	Heat flow of model	[W]	89.26	26.95	20.08	16.05	13.40
χ	Point thermal transmittance of fixings	[W/K]	0.003	0.030	0.035	0.039	0.041
U_{eq}	U-value including impact of fixings	[W/m²K]	2.247	0.833	0.688	0.608	0.553
T_{si}	Internal surface temperature of model	[°C]	11.17	16.70	17.42	17.85	18.14
f_{Rsi}	Temperature factor considering fixings		0.559	0.835	0.871	0.893	0.907

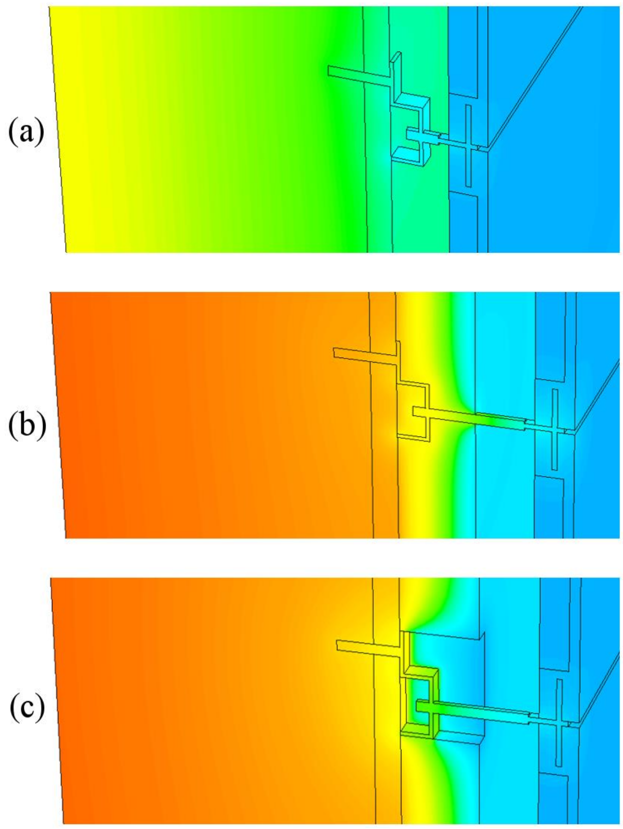

Figure 3. Temperature distribution from numerical model: (a) no insulation, (b) 60 mm insulation with no gap around anchor, (c) 60 mm insulation with an air gap in the projection of the anchor.

Temperature distributions over numerical models are depicted in figure 3. While the case with no insulation (a) has a steep temperature gradient through the concrete, the addition of thermal insulation contributes to isolate the wall from external conditions. However, when a gap in the insulation is present near the anchor (c), the temperature distribution at both concrete and insulation is less uniform and more affected by external conditions than for the case with no gaps in the insulation (b).

5. Conclusions

The thermal performance of an external wall assembly insulated with a ventilated façade system supported by stainless steel anchors has been assessed in this study, using two different methods: simplified one-dimensional calculation and three-dimensional numerical modelling. A plot of the obtained results is presented in figure 4, assessing thermal performance (a) and moisture risk (b) as a function of insulation thickness. In this study, a thermal conductivity of $\lambda = 0.038$ W/mK (representative of a standard mineral wool) has been assumed for the insulation. The cladding materials (high-density geopolymer and wood geopolymer, in the case of the solution assessed) do not contribute to the thermal performance of the façade, as the cavity behind them is ventilated to outside air.

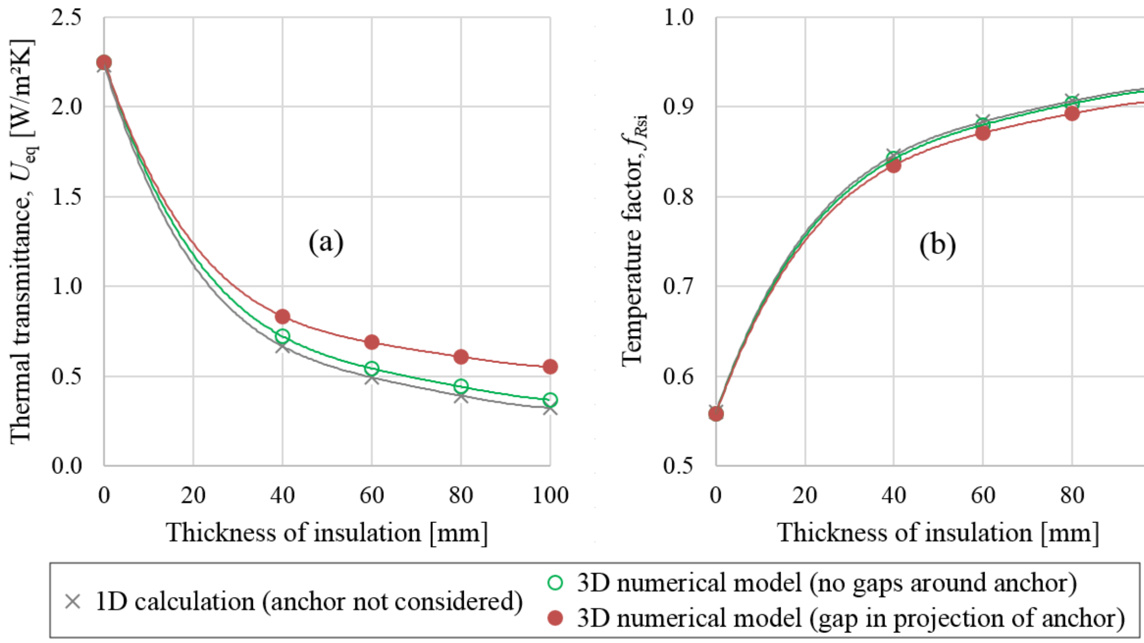

Figure 4. Comparison of results from one-dimensional calculation and three-dimensional numerical modelling, as a function of insulation thickness, for equivalent *U*-value (a) and temperature factor (b).

The overall heat flow across the wall, measured by the thermal transmittance or *U*-value (figure 4a) reduces as insulation levels rise. However, one-dimensional *U*-value calculations do not take account of the multi-dimensional heat flow across the steel anchors: this additional heat flow grows as insulation levels increase, and can become significant for well insulated walls. If the insulation is tightly pressed around the anchors, with no air gaps present, the increase in *U*-value compared to one-dimensional calculations ranges from 8.3% for 40 mm thick insulation to 13.7% for 100 mm thick insulation. This increment might be considered reasonable, and appears to be notably advantageous if compared to aluminium-based systems [6].

However, this solution (figure 1b) is very difficult to achieve in practice even when flexible insulants are used, and outright unfeasible with rigid insulants. When gaps in the insulation exist in the projection of the anchor (figure 1c), the increase in *U*-value over the one-dimensional calculation rises substantially, ranging from 25% for 40 mm thick insulation to 70.1% for 100 mm thick insulation, thus diminishing the effectiveness of the thermal insulation in a significant way. In figure 4a, the shape of the curve for the three-dimensional numerical model with a gap in the projection of the anchor flattens for higher insulation levels, indicating that the thermal bridge poses a limit for the achievable thermal performance. Results from thermal modelling show that, when such gaps exist, U-values below 0.4 W/m²K cannot be achieved even with extreme thicknesses of insulation: such an assembly would not comply with U-value requirements for new buildings in many European national, regional and local regulations [5].

The potential for condensation or mould growth over internal surfaces depends on indoor and outdoor ambient conditions (moisture generation, ventilation, internal and external temperatures), and the resilience of the structure (assessed by the temperature factor). Consequently, temperature factor requirements can vary depending on the harshness of the climate and the indoor humidity load dictated by the use of the building. Guidance sources [10][11] reckon that a temperature factor of $f_{Rsi} \geq 0.80$ should be sufficient to prevent surface condensation and mould growth over internal surfaces for dwellings of normal use.

Regarding moisture risks over internal surfaces, the impact of thermal bridges around anchors seems to be much more limited than for heat flux. Even a low insulation thickness (40 mm) appears to be sufficient to prevent condensation and mould growth over internal surfaces, even in the presence of thermal bridges. This does not exclude the requirement for a ventilation system or strategy that suits the usage of the building, but suggests that ventilated façade systems give greater room for safety than internal insulation approaches.

Three-dimensional calculations in this study are derived from a thermal model of a single anchor. Thus, combined effects due to the vicinity of two or more anchors are not explicitly considered. In theory, this might lead to an overestimation of heat flow in the U-values and a slight underestimation of risk in the temperature factors. However, such deviations are expected to be minor as long as the distance between anchors is longer than the overall thickness of the wall [12]. Furthermore, the numerical models show that the disturbance on surface temperatures remains very moderate, and hence the conclusions stated in the above paragraph remain valid.

In summary, results from this study show that the presence of air gaps around anchors can compromise the thermal performance of the ventilated façade system, resulting in an unforeseen increase on energy consumption if calculations have been based on simplified one-dimensional calculations (as is typically the case). Ensuring the continuity of insulation around anchors is thus a critical necessity for the effective thermal performance of this type of ventilated façade systems. In practice, this implies that flexible insulants need to be used and wrapped with care around each anchor. Pre-assembled anchoring systems including insulation and/or thermal breaks might also be developed to further mitigate these thermal bridges.

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