

Conjugate Heat Transfer in an Adaptive Façade

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Abstract

As a boundary between interior and exterior, the building envelope and its thermal properties are crucial for heat loss and indoor comfort. Dynamic building envelopes offer the potential to optimize buildings in terms of energy efficiency, save resources, and adapt to the needs of users. EnergySkin is a designed dynamic building envelope, that actively controls heat flow through existing façades by regulating the external wall temperature. Developed as a serial solution, it comprises a mounting system and façade modules. The basic element of the façade modules is an insulated glass unit (IGU). A contacted low-emissivity glass coating functions as an electrical heater. The necessary energy is obtained from photovoltaics integrated into the IGU and from supporting battery storage units included in the mounting system. This paper presents the analysis of internal heat flows, temperatures profiles and fluid flows using numerical methods and computational fluid dynamics. Partial investigations focus on the subsystems of the glazing centre and edge as well as the mounting system. The overall system is examined analysed as a conjugate heat transfer between EnergySkin, the existing structure and an airgap required to compensate for unevenness in the façade. The total results are discussed in regards to its thermal behaviour in the context of heat loss and output demand. Finally, directions for future development of Energy Skin are outlined.

Keywords

Adaptive façade, building physics, heat transfer, wall temperature regulation

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1. Introduction

1.1. State of the art

Facades serve as the interface between the exterior environment and the building interior. A primary function of facades is to minimize thermal transmittance, thereby playing a crucial role in maintaining indoor thermal comfort and enhancing energy efficiency. Due to targets for carbon neutrality, the energy-efficient retrofit of facades represents a key strategy to address the insufficient quality of existing building stock (European Commission 2024). Adaptive facades can improve both energy performance and occupant comfort by providing variable properties in response to environmental conditions (Almesbah and Wang 2025). Adaptive features may encompass all functional aspects of a façade. With respect to improving energy efficiency of the building, the capacity to dynamically adjust thermal properties is key.

Adaptive facades with dynamic thermal properties can be classified into systems with latent heat storage, variable solar absorptance, air-flow based dynamic walls, and dynamic insulation (Juaristi and Krarti 2024). Two approaches are applicable for a dynamic insulation solution. Either the thermal conductivity and therefore the heat transfer coefficient are variable or the solution changes the temperature difference across the façade component (Yang and Chen 2022). Examples of switchable thermal conductivities include systems with replaceable or removeable layers (Pflug et al. 2018), fluid based thermal diodes (Pugsley et al. 2020), or phase change materials (Togun et al. 2025). Dynamic insulations, which focus on the temperature difference include systems using thermoelectric modules or pipe embedded systems (Yang and Chen 2022). As an example for the first system, a thermoelectric façade consists of Peltier elements connected to heat conducting layers close to the interior and exterior of the façade. The Peltier element transports heat from one conducting layer to the other bridging the static insulation. Despite recent advances, currently developed thermoelectric systems still exhibit limited energy efficiency (Blum et al. 2023). The LEXU II project, an example of a pipe embedded system, has proven the feasibility of façade integrated heat sources to control the heat flow. It utilized low-temperature water circulation in pipes embedded between the existing structure and additionally applied static insulation (Groß and Schmidt 2020). It relied on heat pumps and grid electricity. Subsequent systems like AktivDHKS include on-site photovoltaic generation (Weiß et al. 2024).

EnergySkin is a proposed system that is supposed to regulate external wall temperature similar to pipe-embedded systems. Unlike these systems, it employs an electric heat source to eliminate reliance on moving components and liquids. Additionally, the integration of photovoltaics directly into the façade and battery storage enable a high degree of self-sufficiency. The system is designed as a modular system. The active modules are based on an insulated glazing unit, due to the capabilities of enclosing the photovoltaics within and using developed coatings as the heat source. (Uhlig et al. 2026)

Simulations of the energy demand and yield for EnergySkin demonstrate the system's potential to achieve energy self-sufficiency while reducing heat loss from the interior to levels comparable to static insulation, despite having around half the thickness (Stoppel et al. 2026). The energy flow through the façade in performed simulations was considered to be one-dimensional, estimated convection and transmissions in fluids by using equivalent thermal conductivities and neglected radiative transmissions through transparent solids. Therefore, internal heat flows and temperatures profiles need to be examined accounting for multi-dimensional heat flow as well as heat flow by convection and radiation.

1.2. Building physics

The heat transfer coefficient, U-factor, is used as key parameter of the thermal insulation quality (DIN EN ISO 6946). Conventionally layers of materials with low thermal conductivities and high layer thickness are used in the façade to decrease the U-factor. Assuming static conditions the overall heat flow is the product of multiplying the temperature difference times U-factor. The resulting heat flow has to be constant across all component layers in accordance with the conservation of energy.

An external wall temperature regulation is manipulating the heat flow through a façade by artificially decreasing the temperature difference between the interior and the exterior. This can be achieved by introducing an additional heat source inside the building component. First, heat flows from the interior to the heat source. Secondly, heat flows from the heat source to the exterior. Both heat flows are dependent on the temperature difference of the respective section. Compared to the conventional approach the decisive factor is the temperature at the heat source. A higher temperature results in a lower heat flow from the interior and a higher heat flow to the exterior. As consequence the introduced heat has to compensate these changes. The needed heat output at the state of equilibrium can be described by formula 1:

$$\text{heat output} = \text{heat flow}_{\text{heat source} \rightarrow \text{exterior}} - \text{heat flow}_{\text{interior} \rightarrow \text{heat source}} \quad (1)$$

This considers a one-dimensional perspective and concentrates on conduction-dominated heat transfer. The assumption is valid for an infinite wall composed of homogeneous layers. Consequently, the heat source must be a heating layer to achieve uniform external wall temperature regulation. However, since the wall is finite in size, potential geometric thermal bridges may occur. Additionally, if the layers are not homogeneous, material-related thermal bridges can arise. If fluids or transparent materials are included in the construction, heat is also transported by radiation and by convection. Heat transfer through radiation occurs via electromagnetic waves, allowing energy to be emitted, absorbed, transmitted, or reflected by layers. Natural convection involves the transfer of heat through the bulk movement of fluids, where warmer fluid regions rise and cooler regions sink, creating convective currents that enhance thermal energy transport. The Grashof number (Gr , formula 2) is the ratio between buoyancy forces and viscous forces. It is dependent from the gravitational acceleration, g , coefficient of volume expansion, β , characteristic length, L , and kinematic viscosity, ν , as well as the difference of the fluid temperature at the surface, T_s , and bulk fluid temperature T_∞ (Awasthi et al. 2025). A lower Grashof number suggest, that natural convection is suppressed by viscous forces.

$$Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2} \quad (2)$$

1.3. Investigated system

EnergySkin is a system currently being developed as an energy-neutral refurbishment solution and using external wall temperature regulation. As a sustainable system it aims at achieving resource efficiency, circularity, separability, durability and structural integrity. EnergySkin is a modular system consisting of a mounting system and façade modules.

The core element of the façade modules is the double-glazed insulation unit with an argon filled cavity, acting as passive insulation. Within the IGU two active layers are contained. A low-emission coating based on aluminium-doped zinc oxide with electrical contacts is used on the third layer as a heat source for regulating the exterior wall temperature. On the second layer photovoltaic cells are integrated to provide the required operating electricity for the external wall temperature regulation as system-

integrated energy source. Battery storage is employed to guarantee that, during times of inadequate photovoltaic output, the excess energy generated during periods of surplus production is used to sustain operation. (Uhlig et al. 2026)

The mounting system provides a durable and removable attachment of facade modules to the existing structure. To keep on-site labor to a minimum a plug-and-play approach is focused, which allows for the efficient installation of prefabricated modules with releasable dowel or screw connections. Required cables for the heating layer, photovoltaics and sensors can be routed through the mounting system and connectors to the functional layers coming out of the sealed IGU are also contained within the mounting system. To allow the façade module to be clamped by the mounting system, a sealed airgap is kept between the existing wall and the façade module. This airgap has the added benefit of acting as passive insulation. The mounting system has to create this airgap while compensating the tolerances of the existing wall. A crucial requirement – and part of the presented research – is the prevention of thermal bridges, which could diminish the effects of the external wall temperature regulation.

Figure 1 is a schematic close up of EnergySkin at the mounting system with the considered heat flow mechanisms. The heating layer, low-E-coating, is indicated by a yellow dotted line.

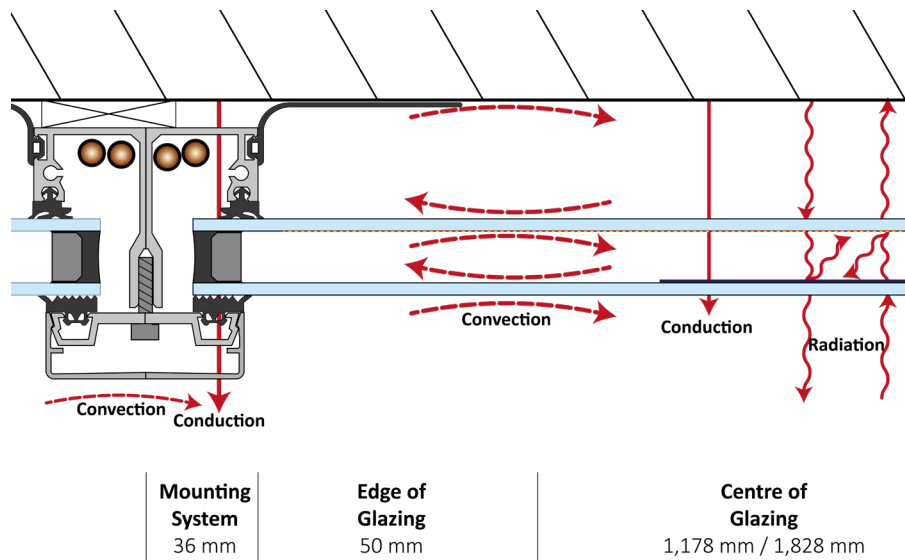


Fig. 1: Considered heat flows within EnergySkin.

2. Methods

2.1. Overall approach

In accordance with ISO/DIS 15099, the system is subdivided into three subsystems to analyze heat transfer mechanisms: the center of the glazing, the edge of the glazing, and the mounting system (Fig 1). Preliminary fluid dynamics simulations are conducted to study conduction and convection within the air gap, defining convective boundary conditions.

The centre of the glazing is assessed using the software tool “WINDOW”, which models one-dimensional, steady-state heat transfer. This covers conduction in solids by thermal conductivity, conduction and convection in fluids by empirical coefficients and radiation by coefficients derived by the Stefan-Boltzmann law. Since the glazing edge and mounting system are thermally coupled, they

are analysed jointly using the software tool “THERM”. This analysis solves a two-dimensional heat transfer using the finite element method. Within glazing and frame cavities, convection and radiation are incorporated by an equivalent conductivity, increasing the fluids thermal conductivity with convection and radiation effects. Convection effects for the gap of the IGU are imported from WINDOW, while those within the mounting system are directly calculated by THERM.

The photovoltaic system integrated within the IGU is modeled as a shading element. The mounting system is simulated four times in total, reflecting that tolerance compensation is applied solely to the left jamb and the head, while a cavity is assumed for the sill and the right jamb. The U-Factor of the entire system is derived by integrating the results obtained from the three subsystems with their components, weighting their contributions according to their respective areas. The total U-factor is calculated following formula 3.

$$U_{Total} = \frac{\sum U_{subsystem, component} \cdot A_{subsystem, component}}{A_{Total}} \quad (3)$$

Obtained U-factors for the subsystems and the determined heat generation according to Formula 1 are used for a two-dimensional steady-state fluid dynamics simulation in Ansys Fluent. This is used to investigate the flow behaviour in the air layers and the distribution of temperatures and heat flows across the height of the façade.

2.2. Boundary conditions, geometry and material properties

Figure 2A gives an overview of the assigned boundary conditions to the surfaces. As the mounting system is in direct contact with the existing structure, the temperature at the contact surface should be defined as boundary condition 1. Since the existing structure is assumed to be in a tempered state due to external wall temperature regulation, a homogeneous constant temperature of 20 °C is targeted. However, because the software tool does not allow for a boundary condition with a constant temperature, a convective boundary condition with a bulk temperature of 21 °C and the highest possible film coefficients is used as a substitute. The film coefficients were empirically determined as 28 W/(m²K) at the head and 50 W/(m²K) at the other components, as THERM could not complete the calculations with higher values.

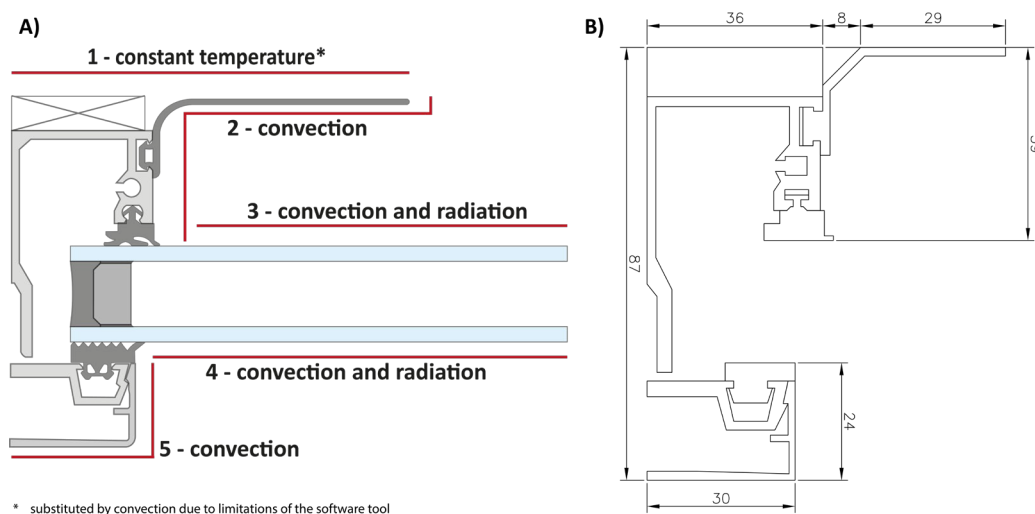


Fig. 2: A) Numbered boundary conditions B) Dimensioned geometry of the simulated mounting system.

A preliminary fluid dynamics simulation studied the convective and conductive effects of the air gap between the existing structure and the IGU. The simulation was performed with Ansys Fluent. The gap was modelled two-dimensional simplified as a rectangle with a height of 2,000 mm and a depth of 40 mm. The flow model chosen was laminar and the Boussinesq approximation was used with air assumed as an ideal gas. The boundary conditions were selected with constant 20 °C for the existing structure and constant 16 °C for the second pane of the IGU with external wall temperature control. The upper and lower boundaries are adiabatic. The resulting heat flux was 3.1 W/m² with an air gap temperature of 18 °C. According to formula 4 (DIN EN ISO 7345) the film coefficient can be assumed as 1.6 W/(m²K). This film coefficient as well as the air gap temperature are the selected convective boundary conditions 2 and 3 for surfaces adjacent to the air gap.

$$\text{Heat flux} = \text{film coefficient} \cdot (\text{bulk temperature} - \text{surface temperature}) \quad (4)$$

The convective boundary conditions 4 and 5 are selected as a temperature of -5 °C in accordance with film DIN 4108-3 coefficients of 25 W/(m²K) in accordance with DIN EN ISO 6946. As the temperature of the existing wall is set as 20 ° the effective room temperature is the same for the radiative boundary condition 3. The effective room emissivity is 0.9 following assumption of the emissivity of the exterior surface of façade from the DIN EN ISO 6946. For the radiative boundary condition 4 an effective sky temperature 11 K below the ambient temperature, thus -16 °C, with an effective sky emissivity of 1 is adopted from DIN EN ISO 52016.

The grid dimension of EnergySkin is 2,000 mm in height by 1,350 mm in width. With a height of 1,975 mm and a width of 1,325 mm the IGU is smaller. The IGU is modelled as system of 5 layers. The first layer is a generic clear glass with a thickness of 4 mm. The second and fourth layer are gaps with a 90 % argon fill with a thickness of 0.1 and 16 mm respectively. The third layer is the modelled photovoltaics. To the top and bottom edge of the glazing a distance of 29 mm and to the left and right edge a distance of 60 mm is assumed for the photovoltaics, which covers 92 % of the remaining area. They are substituted by a closed venetian blind, covering equal area, with a height of 80 mm, a spacing of 84 mm and a thickness of 1 mm. The fifth layer is Pilkington K-Glass with a thickness of 4 mm as it has the required aluminium-doped zinc oxide layer used as the electrical heating layer. The dimensions of the simplified geometry of the modelled mounting system in THERM are visualized in figure 2B.

Material properties for the modelled glazing are retained from WINDOWS database. The photovoltaics are considered as a shading material with no transmissions, reflectance of 0.04 and emissivity of 0.85 at the front, reflectance of 0.70 and emissivity of 0.90 at the back (Lee and Tay 2012) and an average thermal conductivity of 11.6 W/(m·K) (Lamaamar et al. 2022). The mounting rail, clamp and cover are made from aluminium with the cover being painted. The weather stripping and seals are made of ethylene propylene diene Monomer (EPDM). To compensate tolerances in the existing structure rigid polyurethane foam is used. The Spacer of the IGU is aluminium with a fill of silica gel as desiccant, a primary seal of butyl rubber and a secondary seal of polysulfide. Table 1 gives an overview of the material properties. The thermal conductivities are taken from DIN EN ISO 10456 while the emissivity from THERMs material library have been kept.

Table 1: Materials with properties.

Material	Thermal Conductivity [W/(m·K)]	Emissivity
Aluminium	160	0.2 / 0.9 (painted)
EPDM	0.25	0.9
Rigid polyurethane foam	0.05	0.9
Butyl rubber	0.24	0.9
Polysulfide	0.40	0.9
Silica gel	0.13	0.9

For the fluid dynamics simulation, the system geometry was simplified to consist solely of rectangular elements. Two air gaps, each measuring 1928 mm by 39 mm, were modelled and separated by a mounting system sized 72 mm by 87 mm, with half of the mounting system enclosing the top and bottom. The edges of the glazing have a height of 50 mm, while the centre has a height of 1828 mm. In terms of depth, the glazing domains are divided into two layers: a 4 mm layer located at the air gap and a 20 mm layer. The 4 mm layer includes the heat generation to simulate external wall temperature control. At the exterior surface boundary condition 5 is assigned, while the top and bottom surfaces were treated as adiabatic. The interior boundary condition was modelled as convection, with a bulk temperature of 22.5 °C and a film coefficient of 6.9 W/(m²K), behind a wall with a thickness of 360 mm and a thermal conductivity of 0.543 W/(m·K). These values correspond to an existing, unrenovated wall characterized by a U-value of 1.2 W/(m²K), experiencing a heat flux of 3.1 W/m² and a surface temperature of 20 °C, consistent with the preliminary fluid dynamics simulation.

The optimised global mesh has a uniform element size of 1.5 mm and is predominantly quadrangular. In addition, prismatic boundary layers were generated, encircling the air gaps. The k-omega SST (Shear Stress Transport) turbulence model is used for the numerical description of the turbulent flow. Gravity was taken into account with a value of 9.81 m/s² in the vertical direction. The air is modelled in a simplified manner as an incompressible ideal gas. The properties of the air are specified in accordance with DIN EN ISO 10456 with a specific heat capacity of 1008 J/(kg·K) and a thermal conductivity of 0.025 W/(m·K) and, according to the Fluent database, with a dynamic viscosity of 1.7894·10⁻⁵ kg/(m·s) and a molecular weight of 28.966 kg/kmol.

3. Results

For the centre of the glazing a U-factor of 1.15 W/(m²K) is calculated. In the solar spectrum 3 % of the light is transmitted, while 11.6 % is absorbed in the first pane, 74.8 % in the photovoltaics and 0.7 % in the second pane. The centre of the glazing has a height of 1.828 m, a width of 1.178 m and thus an area of 2.15 m². The obtained U-factors of the edge of the glazing and the frame are listed in table 2, as well as the area perpendicular to the heat flow of each subsystem. The U-factor of the mounting system corresponds to a width of 36 mm, while the U-factor of the edge pertains to 50 mm of the glazing that extends beyond the mounting system. The area-weighted U-factor for the subsystems results to 1.39 W/(m²K).

Table 2: U-Factors and dimensions of each component of the subsystems.

Subsystem	Component	U-Factor [W/(m ² K)]	Length [mm]	Area [mm ²]
Edge of glazing	Head	1.20	1,228	61,400
	Jamb, left	1.19	1,878	93,900
	Jamb, right	1.22	1,878	93,900
	Sill	1.21	1,228	61,400
Mounting System	Head	3.94	1,314	47,304
	Jamb, left	4.01	1,964	70,704
	Jamb, right	3.52	1,964	70,704
	Sill	3.69	1,314	47,304

Using the obtained U-factor of 1.39 W/(m²K), a heat flux of 3.1 W/m², and the target temperature of 20 °C for the existing structure, Equation 1 calculates a required heat generation of 31.65 W/m² to serve as the boundary condition for the fluid dynamics simulation. This corresponds to a volumetric heat generation rate of 7,912.5 W/m³, based on a layer depth of 4 mm. Simulation results indicate a total area-weighted heat flux of 1.6 W/m² from the interior and 31.3 W/m² to the exterior. Consequently, the heat generation compensates for transmission losses at a level exceeding that predicted by the initial consideration. EnergySkin reduces the transmission losses equivalent to a U-Factor below 0.06 W/(m²K).

The temperature profile (figure 3A) shows that the air gaps exhibit an almost homogeneous temperature distribution, averaging 21.8 °C, with cooler regions located at the top and bottom of each gap. Due to this higher temperature, the heat flux from the interior into the air gaps is less than 0.9 W/m². In contrast, the mounting systems experience significantly higher heat fluxes; for instance, the central mounting system exhibits an interior heat flow of 8.3 W/m² and an exterior heat flow of 28.8 W/m². At the center of the glazing, the heat flow closely corresponds to the heat generation, with a value of 31.5 W/m². However, at the edges, the heat flow to the exterior is lower, measuring 24.8 W/m² and 24.0 W/m², with the higher value associated with the upper edge of the lower module. In regards to the vertical direction the thermal bridge effect becomes evident, with a heat flow of 43.9 W/m² and 17.4 W/m² from air gaps as well as 10.2 W/m² and 9.3 W/m² from the glazing edge into the mounting system.

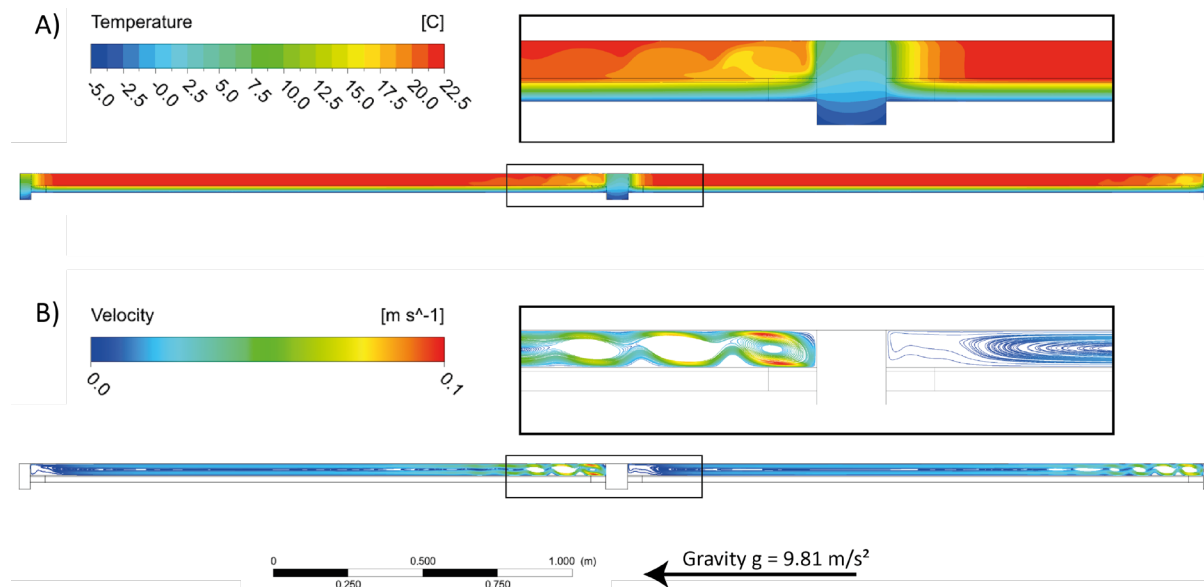


Fig. 3: Temperature and velocity profiles of EnergySkin with two modules.

Overall, the airflow velocity within the air gaps (figure 3B) remains low, averaging 0.01 m/s. The velocity increases with height inside each gap, reaching a maximum of 0.07 m/s near the top. Additionally, flow turbulence intensifies at the upper regions of the air gaps, characterized by the formation of smaller vortices. This behavior is also evident in the temperature profile, which shows a layered temperature distribution near the bottom and a more diffuse profile toward the top. The placement of the heating layer to the exterior contributes to minimizing convection currents by reducing the temperature gradient across the air gap. This is supported by the dependence of the Grashof number on the temperature difference described in formula 2. Consequently, the design-specific air gap functions more effectively as a stationary thermal insulation layer with conduction dominated being more relevant.

4. Conclusion and future works

For the EnergySkin-system a static U-factor of 1.39 W/(m²K) was obtained by division in to subsystems of the mounting system, the edge, and the centre of the glazing. Including the dynamic effect of the external wall temperature regulation with a power of 31.65 W/m² EnergySkin improves the U-Factor of the overall façade to be below 0.06 W/(m²K). As a dynamic insulation this property can be changed with varying power and by different boundary conditions.

With respect to the temperature profile and airflow within the air gap, the simulation demonstrates that the location of the heating layer suppresses convection, thereby enhancing thermal efficiency. Increased external wall temperature control synergistically amplifies this effect, leading to a further decrease in convection. The mounting system functions as a thermal bridge primarily in the vertical direction of the external wall temperature regulation, with a lesser effect on the horizontal heat flow from the interior. However, given the proportion between the module and mounting system areas, the overall detrimental effect remains limited in the analyzed model. A three-dimensional simulation is required to more accurately capture the temperature distribution and incorporate corner effects.

The U-values determined for the individual subsystems and the updated value for the heating layer output will be used for more precise quantification of energy requirements in building simulations.

Here, the wall sections must be differentiated according to the subsystems in order to take into account the influence of the mounting system and effects of the glazing edge of the façade module. The next step is to experimentally validate the temperature profiles and fluid flows in order to further verify the theoretical models and simulation results and optimise them if necessary.

The results obtained from the numerical analysis thus form the basis for further, detailed investigations that enable a well-founded evaluation of the thermal properties of EnergySkin and thus contribute to the targeted optimisation of the overall concept.

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