

Movable Insulation Systems in Building Envelopes: A Review of Heat Transfer Mechanisms

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Abstract. Movable insulation systems have attracted growing interest as a strategy to enhance the thermal adaptability of building envelopes and improve building energy performance under variable climatic conditions. These systems include various solutions that modify the thermal configuration of the envelope through the displacement or reconfiguration of insulating components. Existing studies have examined such systems across different climates, building types, and design approaches. However, existing literature reviews are often organised according to typological or construction-based classifications, rather than by the underlying heat transfer mechanisms that govern their thermal behaviour.

This article presents a review of movable insulation systems with a particular focus on the underlying heat transfer mechanisms through which they affect envelope performance. The review analyses how movable insulation influences conductive, convective, and radiative heat transfer, and how these mechanisms relate to the thermal behaviour of the envelope in different operating modes. The review also addresses how performance has been modelled and assessed in the literature, identifying this as a comparatively underexplored dimension of movable insulation research.

By structuring the literature around fundamental heat transfer processes, the review aims to provide a coherent framework for interpreting existing research, identifying knowledge gaps, particularly in modelling and performance evaluation.

Keywords: Adaptive façades, movable insulation, dynamic envelopes, review.

1 Introduction

Movable insulation systems have gained increasing attention as a strategy to enhance the thermal adaptability of building envelopes under variable climatic conditions. By enabling the dynamic reconfiguration of insulating components, these systems can

overcome the limitations of static insulation behaviour, switching between high and low thermal resistance states as needed. Therefore, this feature is relevant under the increasing climate variability and extreme temperature events projected for many regions.

Existing studies have examined such systems across different climates and building types, often focusing on specific solutions such as rotating panels, retractable screens, or cavity-based configurations.

The novelty of this review lies in its analytical approach, which examines *movable insulation* systems through the lens of the fundamental heat transfer processes that govern their thermal behaviour. By approaching the review from this angle, one can identify patterns in how these systems manage heat flow. To establish a consistent framework, the review clarifies key conceptual distinctions between *movable*, *removable*, and *dynamic insulation*, positioning *movable insulation* within a broader taxonomy of adaptive façade technologies. It then analyses how representative systems modulate heat transfer and examines how performance has been modelled and assessed. This framework aims to interpret existing research and identify knowledge gaps.

2 Scope and Methodology

This review was conducted following a structured four-phase approach, in line with the PRISMA 2020 [1] statement to ensure transparency and reproducibility.

Four databases were searched (Scopus, ScienceDirect, IEEE Xplore, Web of Science) for the period January 2000 to March 2026 using the Boolean query: ("movable insulation" OR "removable insulation" OR "switchable insulation" OR "dynamic insulation"). The search yielded 1048 unique records after duplicate removal. Supplementary searches included Google Patents (4 key patents), Google Scholar (one technical report, one master's dissertation, one doctoral thesis, one conference paper).

A preliminary survey revealed terminological ambiguity. Thus, clear definitions were established for *movable insulation*, *removable insulation* and *dynamic insulation*. These definitions served as the analytical lens for the review.

Publications were considered eligible if they: (i) described a building envelope system involving the physical displacement of an insulating component; (ii) provided detailed information on the underlying heat transfer mechanisms or thermal behaviour; and (iii) included experimental validation, numerical modelling, or documented building applications. As a result of the selection process, 47 publications were considered potentially relevant. Full-text assessment narrowed these to 13 representative studies. Reference lists were cross-checked, confirming that no additional primary studies were found.

The final selection comprised 20 documents (13 studies plus 4 patents, 1 technical report, 1 master's thesis, 1 doctoral thesis). Data were extracted according to three guiding questions: (i) How does geometric reconfiguration affect thermal resistance? (ii) Which heat transfer mechanisms are activated or suppressed in each operational mode? (iii) How have these mechanisms been modelled and evaluated?

Four systems met the strict definition of *movable insulation*: rotating external panel

system (REPS), rotating internal panel system (RIPS), retractable screen system (RSS) and convection control panel system (CCPS). These are analysed in detail in Sections 4.1–4.4.

3 Terminology and Conceptual Boundaries

Given the inconsistent and often overlapping use of expressions related to adaptive insulation strategies in the literature, clear definitions are required. This review distinguishes between *movable insulation*, *removable insulation*, and *dynamic insulation*.

For the purposes of this review, *movable insulation* is defined as a class of thermally adaptive envelope technologies in which a layer or element with high thermal resistance is physically displaced, through rotation, translation, folding, or other repeatable kinematic operations, yet remains part of the building assembly, with the primary objective of modulating the effective thermal conductance of the envelope. Its adaptability arises exclusively from geometric or configurational change at the system level, and not from reversible alterations of the intrinsic thermophysical properties of the insulating material itself. This definition emphasises four key characteristics: (i) the insulating element possesses inherently high thermal resistance in its insulating state; (ii) adaptability is achieved through controlled spatial reconfiguration; (iii) the insulating element remains permanently integrated within the envelope assembly throughout operation (i.e., it is not removed); and (iv) the process is repeatable, enabling reversible transitions between distinct thermal states.

With this definition, a clear conceptual distinction is established in contrast to *removable insulation* which refers to systems in which the insulating element is completely removed from its position of operation and stored elsewhere when not required. This process is typically discrete, often manual, and does not involve continuous or repeatable modulation of the envelope configuration. Examples include seasonal insulation panels or detachable insulating shutters.

Additionally, one should also note that there are also insulation systems in which the thermal resistance (*R-value*) of the insulation layer itself is reversibly altered by intrinsic physical mechanisms of the insulating material [2], i.e. *dynamic insulation*. *Dynamic insulation* is therefore conceptually distinct from *movable insulation* and other adaptive envelope strategies where variable thermal behaviour is achieved through extrinsic means, such as spatial rearrangement, configurational change, or other system-level control mechanisms.

To structure the analysis of *movable insulation* systems, this study adopts an existing hierarchical taxonomy of adaptive thermal façade technologies, organised into successive tiers that distinguish adaptive mechanisms, functional strategies, and technological implementations [2]. Within the first tier of adaptive mechanisms, *movable insulation* belongs to the category of *Adaptive Heat Transfer Control Technologies*. At the second tier, it falls within *Adaptive Heat Flow Modulation Technologies*, encompassing strategies that modulate conductive, convective, and radiative heat transfer through the façade assembly without inducing airflow exchange between adjacent construction elements. At the level of technological implementation, *movable insulation* systems can

be understood as *switchable R -/ λ -value technologies*, in which the effective thermal resistance of the façade is altered through controlled changes in the spatial configuration of insulating elements. For more details on taxonomy of adaptive thermal façade technologies please refer to [2].

4 Heat Transfer Mechanisms in Movable Insulation Systems

As shown in the literature, *movable insulation* is implemented through different technological solutions and envelope assembly configurations and is not associated with a single dominant heat transfer mechanism. The literature survey conducted revealed that four systems correspond to the above definition of *movable insulation* (Fig. 1): the rotating external panel system (REPS) [3], the rotating internal panel system (RIPS) [4], the retractable screen system (RSS) [5], and the convection control panel system (CCPS) [6]. The review therefore examines these systems in detail, with particular emphasis on the heat transfer mechanisms that dominate in each configuration.

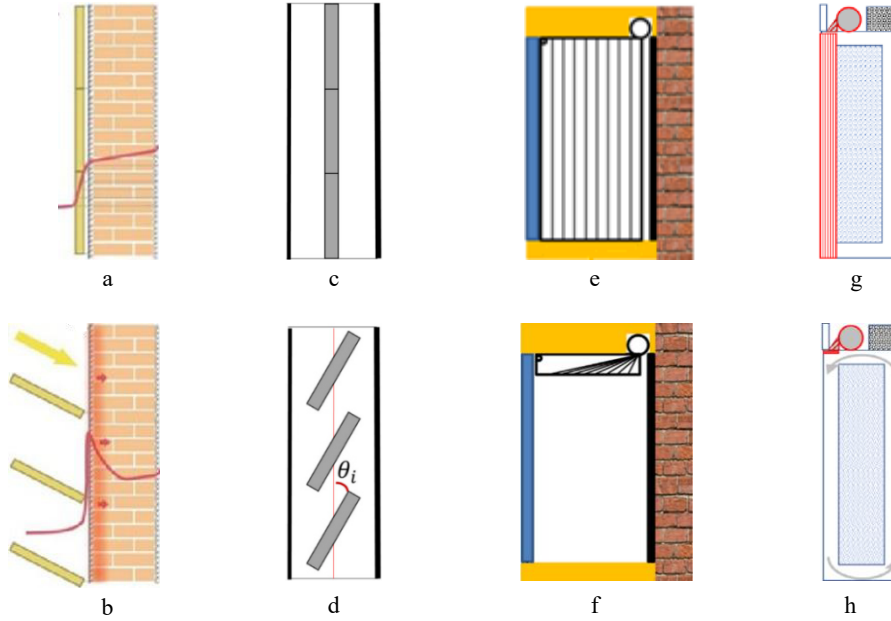


Fig. 1. Systems in insulating (top) and conducting (bottom) states: (a, b) REPS [7], (c, d) RIPS [8], (e, f) RSS [9], (g, h) CCPS [10].

4.1 Rotating External Panel System (REPS)

Patented by Schwarzmayer [3] and developed in Austria, the REPS is a documented implementation of *movable insulation* applied to the exterior of a building envelope [7]. It consists of rigid insulation panels that rotate about a horizontal axis, allowing switching between thermally resistive (Fig. 1a) and conductive modes (Fig. 1b). Its

operating principle exploits the thermal inertia of the external wall, modulating heat transfer through geometric reconfiguration. In the closed position, the panels form a continuous insulating layer with high thermal resistance, thereby reducing conductive heat losses. A thin air cavity remains between panels and wall, where convection is limited and radiative exchange is minimised by a low-emissivity coating on the inner panel surface.

During the heating season, when solar conditions are favourable, the panels rotate to an open position, exposing the high-absorptance wall to direct solar radiation. The low-emissivity inner surface of the panels reflects part of the incoming shortwave radiation onto the wall, enhancing solar gains. These gains are absorbed and stored in the wall's thermal mass, with heat released inward after a time lag, reducing heating demand. The system therefore actively modulates conductive and radiative heat transfer mechanisms, and heat storage, as a function of environmental inputs. To optimise this modulation, the system incorporates a self-learning control logic.

During the cooling season, the operational logic is reversed. The panels remain closed during daytime to limit conductive and radiative heat gains. At night, they open to promote heat dissipation from the wall to the exterior, primarily through longwave radiative exchange with the sky and convective cooling.

Burdajewicz [11, 12] developed a transient Simulink/Matlab model for Vienna's climate (Dfb – Warm-summer humid continental climate according to the Köppen-Geiger climate classification), incorporating control strategies based on temperatures and solar radiation. Simulations [12] showed that the base REPS configuration reduces annual heating demand by $\approx 23\%$ and cooling demand by $\approx 64\%$ compared to a conventional 12 cm insulated wall. Parameter studies also explored the influence of design parameters such as a glazing layer or selective absorber coatings.

The system was implemented in a demonstration building (“Gartenatelier”) under the “Haus der Zukunft Plus” programme [7], where monitoring confirmed improved thermal performance with low electrical consumption for actuation and control.

REPS is commercially available, indicating Technology Readiness Level (TRL) 9.

4.2 Rotating Internal Panel System (RIPS)

Krarti patented a *movable insulation* system for sealed building envelope cavities [4]. It consists of multiple insulating elongated panels fixed to parallel rotational axes, enclosed between inner and outer claddings, forming non-ventilated air cavities [8].

The operating principle relies on panel rotation to modulate heat transfer, particularly convection. In the 0° position (panels aligned vertically; Fig. 1c), the panels create a continuous insulating barrier that segments the cavity into inner and outer chambers. In this configuration, heat transfer is primarily governed by conduction through the panel material and by radiation across the air gaps, while convection is confined within each chamber by cavity thickness and boundary conditions [4, 8]. As the panels rotate (Fig. 1d), convective exchange begins to develop between chambers. At the *disconnect angle*, θ_d (depending on panel geometry), the panels no longer overlap, allowing free air circulation. In the 90° position (panels perpendicular to the surfaces), the system exhibits its lowest thermal resistance, with heat transfer dominated by convection

within the now-connected cavity and radiation between the boundary surfaces [4, 8].

Thermal performance was evaluated experimentally and numerically [8]. Using a calibrated hotbox (ASTM C1363 and ISO 8990), the thermal resistance was measured for various panel angles. The prototype comprised seven polyisocyanurate foam layers (1.02m x 0.25m x 0.05m) that rotate synchronously via an actuator. The results showed a reduction of over 50% in wall *R-value* at the disconnect angle ($\approx 15^\circ$), and an overall reduction of 83.5% between fully closed and fully open positions. A validated ANSYS Fluent CFD model confirmed these findings, with relative errors ranging from 0.53% to 8.05% depending on the panel angle θ_i [8], confirming that the gradual opening enhances convective heat transfer. Sensitivity analyses revealed that performance depends significantly on cavity thickness and panel dimensions [8].

The 3R2C modelling approach [13-15] has been used to assess RIPS across multiple climates for residential and commercial buildings [13-18]. For residential wall-integrated RIPS, cooling savings were highest in oceanic climates (98.7% in St. Hubert, Belgium), however heating savings remained modest in this climate (3.7%) [16]; conversely, heating savings were highest in continental climates (56.1% in Golden, USA) where high cooling savings are also noted (69.3%) [13]. In very cold climates, RIPS offers limited savings, while in very hot arid climates, cooling savings are moderate. Additionally, heating savings can be very high when integrated with other technologies [13, 18]. In commercial buildings, RIPS were evaluated either as standalone technologies [18] or as part of integrated adaptive packages [17].

RIPS is at TRL 4, with its performance extensively validated through parametric simulations, CFD analysis, and multiple peer-reviewed studies across diverse climates [8, 13, 14, 16-18]; however, long-term field validation is still missing, and its experimental validation has been performed only under a single boundary condition [8].

4.3 Retractable Screen System (RSS)

Patented by Kvasnin [5], the RSS consists of retractable insulating screens within a cavity, embodying the concept of *movable insulation* defined in Section 3. Although consistently referred to in the literature as *removable insulation* [9, 19, 20], the screens remain an integral part of the envelope: they retract into a drum rather than being physically removed, satisfying all four criteria of *movable insulation*.

The system can be mounted in front of either opaque or glazed building envelopes, forming a closed cavity with an additional external pane [5]. It consists of a series of parallel vertical screens, such as metallized PET, which can be rolled onto a drum or unrolled [9]. In the insulating state (Fig. 1e), the extended screens create multiple narrow closed air cavities in series. Heat transfer occurs primarily through conduction across the thin, contained air layers (where convection is prevented), with the radiative component minimized by the low-emissivity metallized surfaces. In the conducting state (Fig. 1f), the screens are retracted, resulting in a single large air cavity that offers low thermal resistance. In this configuration, heat transfer is dominated by convection within the cavity and radiation between the boundary surfaces.

Measurements from a prototype, conducted in accordance with ISO 8302:1991, reported a *U-value* ranging from 0.35 to 0.45 W/(m²·K) in the insulating state, depending

on the mean temperature and temperature difference [9]. The theoretical optimal performance calculated following ISO 15099:2003, reaches about $0.14 \text{ W}/(\text{m}^2 \cdot \text{K})$, indicating high thermal resistance potential. In the conducting state, the system offers low thermal resistance with a U -value of $\approx 2.7 \text{ W}/(\text{m}^2 \cdot \text{K})$; slightly varying between wall ($2.76 \text{ W}/(\text{m}^2 \cdot \text{K})$) and window ($2.70 \text{ W}/(\text{m}^2 \cdot \text{K})$) applications. Edge thermal losses and air leakage at frame connections were identified as critical performance factors, as air infiltration can compromise the effectiveness of the insulating state.

Dynamic energy simulations using EnergyPlus with climatic data from Stuttgart (Cfb – Temperate oceanic, warm summer climate), demonstrated that the system applied to south-facing façades can reduce the sum of heating and cooling demands by up to 29% in window applications (11% heating, 55% cooling) and 34% in front of massive opaque walls (31% heating, 38% cooling) when using an advanced control strategy. Performance was found to be non-negligibly influenced by thermal mass and façade orientation.

RSS is at TRL 5, with prototypes and numerical studies validated for a Central European climate [9], yet requiring demonstration in real buildings to reach TRL 6.

4.4 Convection Control Panel System (CCPS)

A conceptual system based on controlled convection within a closed cavity was patented by Nestle *et al.* [6], establishing the fundamental principle of using a *movable insulation* panel to modulate natural airflow. The patented configuration consists of two cover panes enclosing a cavity filled with gas, with a translucent insulation panel positioned between them. By moving this panel vertically, the system can either suppress large-scale convection (insulating state) or enable a convective loop around the panel (conducting state), thereby switching the overall thermal resistance [6, 20].

In the conducting state (panel in a vertical middle position, with top and bottom air gaps; Fig. 1h), large-scale spontaneous convection develops around the panel due to the density difference between the front and back gas columns, significantly reducing the overall thermal resistance of the element [20, 21]. In the insulating state (panel at the top; Fig. 1g), the configuration prevents the large-scale convective loop that characterizes the conducting state. The element behaves like a system with three insulating layers: two thin air cavities and an insulation panel. Heat transfer through these confined air layers is primarily by conduction, although weak internal convection may occur depending on the cavity geometry and temperature gradient. Radiative exchange is minimised by the low thermal emissivity of the surrounding surfaces. A detailed nodal model was developed and validated against the experimental measurements [20].

A later development introduced an additional functionality to the system. Nestle *et al.* [10] proposed an evolved configuration that integrates a static translucent insulation panel with an additional rollable screen. This approach aims to optimize the balance between solar gains, insulation, and lighting requirements by enabling combined control of convection (for U -value switching) and solar transmission (for g -value switching). The rollable screen, with its highly reflective surface, can be extended to suppress convection and reflect incident solar radiation, thereby varying the g -value from almost unchanged to nearly zero [10]. This evolution represents a significant expansion of the

original concept, addressing both thermal and optical adaptability.

The first experimental validation of the patented concept [6] was reported by Pflug *et al.* [21], who measured the *U-value* of prototypes with one and two translucent insulation panels using a guarded hot plate apparatus. The investigation covered geometrical parameters (vertical/horizontal air gaps thicknesses, number/thickness of panels, filling gas type). Results showed significant switching capability; for a two-panel prototype, the *U-value* switched from 0.71 W/(m²·K) in the insulating state to 1.44 W/(m²·K) in the conducting state, representing a switching ratio of 2.03. Using CO₂ as filling gas lowered the insulating-state *U-value* and raised the conducting-state *U-value*. Preliminary TRNSYS simulations conducted for an office building in Ludwigshafen (Cfb – Temperate oceanic, warm summer climate), using measured properties of the single-panel prototype, indicated that the system could reduce cooling loads by 22% and annual discomfort hours by 63.2% compared to a well-insulated reference building. An optimized configuration, assuming a higher *U-value* in the conducting state (3 W/m²·K), achieved a reduction of up to 39.1% in cooling loads and 88.6% in discomfort hours, while also improving summer thermal comfort. In more detailed modelling work [20], the potential of using aerogel as the translucent insulation material combined with low-emissivity coatings was explored, achieving a simulated *U-value* of 0.24 W/(m²·K) in the insulating state and 1.22 W/(m²·K) in the conducting state (ratio of 5.2).

The original concept, based solely on convection control as patented [6] and experimentally validated [20, 21], is at TRL 4. The evolved configuration integrating *g-value* control [21] remains at a lower maturity level (TRL 2-3), pending experimental validation of its combined *U-* and *g-value* switching capability.

4.5 Comparative overview of the reviewed movable insulation systems

Table 1 summarises different approaches for the four *movable insulation* systems reviewed, the climatic contexts covered in the respective studies, and TRL.

Table 1. Comparative summary of the *movable insulation* systems reviewed.

System	Approach		Climate	TRL	References
	Numerical	Experimental			
REPS	Simulink/Matlab	Demonstration building	Dfb	9	[3, 7, 11, 12]
RIPS	ANSYS and 3R2C model	Hot-box tests	Several climates ¹	4	[4, 8, 13-18]
RSS	EnergyPlus	Prototype	Cfb	5	[5, 9, 19, 20]
CCPS ²	TRNSYS	Prototype	Cfb	4	[6, 10, 20, 21]

Notes: ¹ Several Tropical, Arid, Temperate and Cold climates; ² Original concept of CCPS.

5 Conclusion

This review has analysed *movable insulation* systems through the lens of fundamental heat transfer mechanisms, providing a framework to interpret existing research and

identify knowledge gaps across four representative technologies: rotating external panel system (REPS), rotating internal panel system (RIPS), retractable screen system (RSS), and convection control panel system (CCPS).

The comparison shows that, *movable insulation* is not governed by a single dominant mechanism, but by different combinations of conductive, convective and radiative heat transfer control depending on the system configuration. A common feature to all systems is the use of air cavities as a thermally resistive medium, with their thermal role being modulated through geometric reconfiguration. REPS is more strongly associated with solar radiation and thermal mass utilisation, whereas RIPS and CCPS rely more directly on the suppression or enhancement of convection within cavities. RSS combines both behaviours through the reconfiguration of enclosed air layers and the use of low-emissivity surfaces. The systems also differ in maturity, with REPS showing the highest level of implementation, RIPS presenting the broadest numerical and experimental assessment, and RSS and CCPS remaining at earlier validation stages. Nevertheless, important knowledge gaps remain. Current models often rely on simplified assumptions for convective heat transfer under transient conditions and asymmetric thermal boundaries. Experimental studies highlight the significant impact of air infiltration, edge thermal bridges and frame connections, aspects often neglected in numerical models but critical in practice.

Future research should therefore focus on improving modelling robustness, expanding climatic validation, and developing more integrated control strategies to support the effective implementation of *movable insulation* systems in buildings.

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