Composite Materials COMMENTARY

Season-adaptive fluid-switched decoupled dual-band electrochromic window

Xiaohu Wu,[1,2,*] Shujuan Liu,[1] Bing-Ying Liu,[3,*] and Haoqiang Ai[4]
[1]Yangtze Laboratory, Wuhan 430205, China
[2]School of Integrated Circuits, Hubei University, Wuhan 430062, China
[3]College of Bioresources Chemical and Materials Engineering, Shaanxi University of Science and Technology, Xi'an 710021, China
[4]Thermal Science Research Center, Shandong Institute of Advanced Technology, Jinan 250100, China
*Correspondence: wuxiaohu@pku.org.cn (X.W.); LiuBingYingXue@163.com (B.L.)
Received: April 9, 2026; Accepted: July 19, 2026; Published Online: July 19, 2026; https://doi.org/10.59717/j.xinn-mater.2026.100228

Citation: Wu X., Liu S., Liu B., et al. (2026). Season-adaptive fluid-switched decoupled dual-band electrochromic window. *The Innovation Materials* **4**:100228.

Buildings account for approximately 40% of global total energy consumption, with windows serving as one of the primary pathways for heat gain and loss in building envelopes.[1] Electrochromic smart windows (ESWs) can dynamically modulate their optical properties under an applied voltage and are therefore considered a promising technology for reducing building cooling and heating loads. However, conventional ESWs operate predominantly in the visible and near-infrared (VIS-NIR) spectral regions, where the electrolyte is typically designed as a static ionic conductive medium, resulting in limited regulation of mid-infrared (MIR) radiation. Furthermore, the intrinsically high emissivity of conventional glass substrates constrains the dynamic modulation performance of the entire device. Since MIR radiation is a key carrier of radiative heat transfer, this limitation impairs the ability of ESWs to achieve comprehensive thermal management across different seasons, especially in regions with large annual temperature differences. An ideal smart window should possess broad-spectrum dynamic modulation capabilities covering both the VIS-NIR and MIR bands to adapt to seasonal climate variations and substantially improve building energy efficiency.

This commentary reviews four representative electrochromic technologies in a progressive order: single-band solar-regulating ESWs, single-band thermal-radiation-regulating ESWs, mechanically-switched decoupled dual-band ESWs, and fluid-switched decoupled dual-band ESWs. We focus on the liquid-flow electrochromic window (LF-ESW) reported by Huang et al.,[2] which achieves decoupled dual-band modulation through the presence/absence of the electrolyte. This LF-ESW features a fluid-switched, decoupled dual-band design. This design represents a milestone, embodying a fundamental paradigm shift toward true dual-degree-of-freedom control. In contrast to thermochromic materials (e.g., VO_2), which exhibit coupled optical responses and limited modulation ranges, this commentary centers on rationally designed decoupled electrochromic systems capable of independent control over solar transmittance and thermal emissivity.

Single-band solar-regulating ESWs modulate VIS-NIR transmittance but maintain a fixed high MIR emissivity (~ 0.9). A representative example is the all-in-one polyoxometalate-based electrochromic glazing reported by Li et al.,[3] which achieves an excellent solar modulation of 86.4% but offers no MIR tunability, failing to suppress radiative heat loss in winter and thus limiting year-round efficiency. In contrast, single-band thermal-radiation-regulating ESWs focus solely on MIR switching. Sui et al.[4] developed an aqueous electrochromic device that reversibly switches MIR emissivity between ~0.07 and ~0.92 ($\Delta\varepsilon \approx 0.85$) via reversible Cu electrodeposition onto a Pt-modified graphene transparent electrode. Because the device lacks an electrochromic layer for the solar spectrum, its solar transmittance remains unchanged, offering no control over solar heat gain. To achieve simultaneous regulation

Figure 1. Overview of challenges and future directions for liquid-flow electrochromic windows.

of both bands, Ding et al.[5] fabricated mechanically-switched decoupled dual-band ESWs. Their device independently controls solar transmittance via an all-solid-state electrochromic stack (ITO/WO_3/$LiNbO_3$/NiO_x/ITO), achieving ΔT≈92% at 650 nm (VIS) and ≈82% at 1500 nm (NIR). MIR emissivity is switched (Δε≈0.6) by physically flipping the window to expose either a high-emissivity glass or a low-emissivity ITO surface. Although decoupled dual-band regulation is achieved, this design introduces moving parts (hinges, motors), requires additional spatial clearance, and creates complex dynamic sealing issues, thereby limiting large-area or facade integration.

The LF-ESW represents a fundamental paradigm shift. Here, the electrolyte serves not only as an ion conductor but also as a switchable MIR emitter. When the high-emissivity electrolyte zinc trifluoromethanesulfonate-propylene carbonate/triethyl phosphate (Zn-TFMS-PC/TEP) fills the cavity, the MIR emissivity reaches 0.93; when the electrolyte is drained, the underlying low-emissivity fluorine-doped tin oxide substrate dominates (ε = 0.19). Solar transmittance is independently controlled by camphorsulfonic acid (CSA)-doped polyaniline (PANI), which modulates the VIS-NIR transmittance from 68.71% to 25.18%, enabling precise regulation of solar radiation input. The core innovation is state switching via fluid dynamics rather than continuous material-property modulation. Compared with the mechanical flipping approach, the fluid-switched design has no macroscopic moving parts, requires no external clearance, and relies on static rather than dynamic seals. This fundamentally reduces the risk of seal failure, although careful engineering remains necessary to ensure long-term leak-free operation.

Despite its promise, the LF-ESW faces three scientific bottlenecks (Figure 1). First, fluid-optical coupling and response time. For large areas, laminar flow leads to non-uniform filling fronts, causing spatial variations in emissivity and optical states across the window, which compromise the consistency of thermal management and visual performance. The response time is limited by fluid displacement (tens of seconds) rather than by the electrochemical process. Second, cyclic durability and long-term stability. Key failure modes include electrolyte leakage (due to thermal cycling), Zn electrode corrosion, and PANI degradation. We propose a durability validation protocol: static immersion (60°C, 90% relative humidity), dynamic cycling (> 2000 cycles), and accelerated aging tests. Third, parasitic energy and system integration. The incorporation of pumps, reservoirs, and control electronics introduces auxiliary energy consumption and system complexity. From a theoretical perspective, the pumping power required for a 1 m^2 window is estimated to be in the range of 1-5 W/m^2, which is only a few percent of the typical window thermal load (50-200 W/m^2, depending on climate and glazing type). Therefore, the net annual energy savings of an LF-ESW are expected to remain positive in most scenarios, provided the switching frequency is moderate. The best-case applications include continental climates with large seasonal temperature differences and buildings with a high window-to-wall ratio (e.g., offices, airports), where the thermal load dominates and the parasitic energy overhead becomes negligible.

Future research should be synergistically advanced along the following directions. First, smart fluid management. Integrating miniaturized sensors to monitor real-time emissivity and fluid distribution, using feedback control algorithms to dynamically adjust pump speeds and valve positions for adaptive uniformity, and employing passive strategies such as hydrophilic microchannels for capillary-driven residual liquid recovery or gravity-assisted filling in vertical installations can reduce pumping energy consumption. Second, electrolyte innovation. Developing a "super electrolyte" that combines high ionic conductivity, a wide electrochemical window, non-flammability, broad-temperature stability, and environmental friendliness can support long-term stable operation under diverse climatic conditions. Third, energy node integration. The LF-ESW can be coupled with semi-transparent photovoltaics to achieve self-powering; further integration with energy storage, sensing systems, and the building's water circulation system can provide self-powered active thermal buffering. Fourth, machine-learning-driven autonomous control. By integrating machine learning, the system can autonomously perceive ambient conditions (e.g., temperature, solar irradiance) and predict optimal switching timing based on multi-source data (weather forecasts, building energy consumption patterns, indoor/outdoor environmental parameters, and electricity prices). This enables the LF-ESW to transition from human-operated on/off control to intelligent, environment-aware autonomous regulation, minimizing unnecessary pumping events and further reducing parasitic energy overhead while maximizing thermal comfort and energy savings. Based on these considerations, we propose three short-term milestones: within 1-2 years, computational fluid dynamics-optimized microchannel designs achieving > 90% uniformity over 0.5 m^2; within 3-5 years, corrosion-resistant electrodes (e.g., stainless steel mesh) and alternative electrochromic polymers demonstrating <10% degradation over 2000 cycles; within 3-7 years, field demonstrations using rule-based control (summer cooling/winter heating) showing a 30% annual reduction in HVAC energy consumption.

In conclusion, this commentary frames the liquid-flow electrochromic window within the dual-degree-of-freedom concept and highlights its fundamental innovation, state switching via fluid dynamics, as a compact, scalable alternative to mechanical flipping. Although challenges remain in fluid uniformity, durability, and system integration, the outlined research directions offer concrete pathways toward addressing global building energy-saving needs. The LF-ESW inaugurates a new era of "living" building envelopes that sense the environment, dynamically adjust, and intelligently interact with their surroundings, much like biological skin. While this path is fraught with technical challenges, it also harbors transformative innovation opportunities, warranting sustained and dedicated exploration by both the research community and industrial stakeholders.

REFERENCES

1. Sun F., Pal R., Eom S. Y., et al. (2025). Fast-switching dual-cathode electrochromic smart windows for year-round building energy savings. *Nat. Commun.* **16**:9569. DOI:10.1038/s41467-025-64962-2
2. Huang Y., Wu S., Zhao S., et al. (2025). A novel liquid flow electrochromic smart window for all-year-round dynamic photothermal regulation. *Energy Environ. Sci.* **18**:1824–1834. DOI:10.1039/D4EE05416D
3. Li H., Zhang J., Liu Y., et al. (2026). Scalable all-in-one electrochromic glazing for full-spectrum solar radiation management. *Nat. Sustain.* **9**:910–920. DOI:10.1038/s41893-026-01823-w
4. Sui C., Pu J., Chen T.-H., et al. (2023). Dynamic electrochromism for all-season radiative thermoregulation. *Nat. Sustain.* **6**:428–437. DOI:10.1038/s41893-022-01023-2
5. Ding Y., Mei Z., Zhang W., et al. (2025). Intelligent electrochromic photothermal regulation for integrated building energy saving. *Energy Environ. Sci.* **18**:10088–10101. DOI:10.1039/D5EE02750K

FUNDING AND ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (22505148, 52576079), Foundation of National Key Laboratory of Computational Physics (6142A05QN24003). The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.