A Large-Area Smart Window with Tunable Shading and Solar-Thermal Harvesting Ability Based on Remote Switching of a Magneto-Active Liquid

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Switchable windows provide intriguing opportunities for addressing the challenges of modern building skins. In particular, indoor comfort and the control of radiative heat transfer into and out of the building require adaptive and tunable solutions for shading and emissivity. Here, a switchable, ultrathin suspended particle device (SPD) for large-area integration with smart facades is presented. The system is based on a fluidic window, manufactured at low cost from a laminate of structured, rolled glass and a thin cover with high surface strength. Loading the circulating fluid with magnetic nanoparticles enables active shading and solar-thermal energy harvesting, whereby the loading state and, hence, the optical properties of the liquid can be controlled through remote switching in a particle collector-suspending device. In the fully shaded state, a typical harvesting efficiency of 45% of the incoming solar power is obtained. For an average solar irradiance of 1000 W m$^{-2}$ during 800 h a$^{-1}$, this corresponds to a solar thermal harvesting capacity in the range of 360 kWh a$^{-1}$ m$^{-2}$. In comparison to alternative SPD concepts, this enables high flexibility and compatibility with established production lines. In addition, there is no need for further electrical contact, transparent conductive layers, or electrolytes.

1. Introduction

In modern architecture, glass remains an indispensable component. Its foremost role is to facilitate interaction between the interior of a building and its environment, relying on the material's high transparency for visible (vis) and infrared (IR) light, paired with superior long-term stability in a wide range of climatic conditions. Glass facades enhance visual comfort and human well-being, but also productivity inside commercial buildings. Associated with the use of glasses, however, is the need for dedicated control of thermal transport, both in heating and cooling scenarios, and the need for seasonal shading, be it for reducing glare or for enhancing privacy. The former is typically achieved through the use of complex multilayer coatings which enable selective reflectivity in the vis and IR spectral region, providing, for example, anti-reflectivity, low emissivity (low-e), or solar protection.$^{[1–3]}$ Such coatings are combined with the high insulation capability of double-, triple-, or even vacuum glazing.

Shading or, more generally, providing the interior with tunable levels of daylight is a secondary function which adds significant complexity. Conventional devices such as blinds, shutters, or curtains provide static optical properties, giving no room for adaptive responses to variable weather conditions. Similarly, glare disturbance is generally decreased at the expense of daylight so that artificial light may have to be used in compensation and despite high exterior light availability. Consequently, the development of systems which enable dynamic control of the natural light flux through glass facades while, at the same time, contributing to drastic reduction of CO$_2$ emission from highly glazed buildings (estimated at around 40% of Europe’s energy demands)$^{[4]}$ is currently in the focus of the smart-window sector.

A wide variety of advanced glazing technologies have been proposed for tailored shading and transparency control, addressing both solar shielding and the reduction of radiative heat loss from the building. Among these are various concepts for switchable windows, in which the optical properties can be manipulated through an external trigger. Electrically actuated glazings include chromogenics,$^{[5–18]}$ AC-powered suspended particle devices (SPD, Figure 1A)$^{[9,17,19–25]}$ and liquid crystal (LC, Figure 1B)$^{[8,16,17,26–31]}$ devices. All these require electrical conductivity on the glass surface, usually obtained through transparent conductive oxide layers (TCOs). Problematic to real-world applications, together with further auxiliary components such as secondary coatings, electrolytes, dyes, sealing layers, and adhesives, the final devices are extremely complex. Besides high cost, the TCO or other...
parts of the system may interfere with low-e layers, thickness requirements, or insulation functions. In addition and specific to the building sector, major issues may occur with process compatibility where extremely flexible window geometries, standardized frames or mountings, and weight limits must be taken into account.

Concretely, limitations of electric devices typically include (1) restriction to a thin layer of immobilized liquid (carrying the switching function), what reduces the device’s expected lifetime, (2) extended relaxation times between opaque and uncolored states (usually several minutes), (3) requirement of a continuous power supply in the transparent state (e.g., resulting in a power consumption of 5–20 W m$^{-2}$),[17] and (4) reduced long-term UV stability and high cost, primarily arising from the TCO. Indeed, tin-doped indium oxide (ITO) as the most commonly employed TCO$^{[17,32]}$ is facing significant issues related to the supply of indium oxide at acceptable cost. Despite the availability of alternative transparent conductors such as poly(3,4-ethylenedioxythiophene) (PEDOT)$^{[32,33]}$ or layers of carbon nanotubes (CNTs),[32] smart-window requirements can presently not be met. While PEDOT suffers from poor environmental stability and noticeable color, CNT layers are still not available for low-cost large-area applications.

Here, we report on SPD devices which do not require an electrical trigger, but allow for both continuous shading and controlled harvesting of solar heat (Figure 1C). This relies on using glass-glass fluidic devices such as recently reported for large-area integration with adaptive facades$^{[34]}$ or flat-panel algae reactors.$^{[35]}$ As shown in Figure 2A–C, this device comprises a finely structured sheet of glass onto which a thin cover sheet with tailored mechanical performance is laminated. A functional liquid with tunable optical properties is flowing through the thus-created channels. The thickness of the overall system is adapted to the one of a single glass sheet in conventional glazings to ensure a fast and uncomplicated integration with present building technologies.

On part of the fluid, a suspension of magnetite nanoparticles in monopropylene glycol is employed. The optical properties of this suspension are controlled through the particle concentration, which is adjusted outside of the window device in a magnetic particle collector, offering precise transmittance modulation over the visible spectrum for a broad variety of facade constructions. In addition to tunable shading, the particle-induced variation in solar energy uptake enables further solar-thermal harvesting. Besides fluid circulation, electrical power is required only on the instance of switching, with the switching time being determined by the particle collector design and the rate of fluid circulation. This provides a new type of SPD for bypassing the previously mentioned limitations of electrical devices and which, in addition to shading, enables solar-thermal energy harvesting.

2. Results and Discussion
2.1. General

Operation of the present SPD relies on loading and unloading a liquid with nanoscale magnetite particles at a
specific particle number density. As a convention, we define the “ON” state as the state in which the fluid contains the minimum (or zero) particle fraction. In the “OFF” state, the particle fraction is at its maximum. This liquid is circulating within the channels of the capillary glass devices as depicted in Figure 1. The design is chosen so that the thickness of the laminated sheet corresponds to the thickness of conventional glass panes in double or triple glazing, that is, 4–6 mm for regular or low-noise windows, respectively. This is a key feature for real-world implementation with regular window manufacture processes. Switching is achieved through an external particle collector-suspender tank in which permanent magnets or electromagnets are used to draw the magnetic nanoparticles from the liquid. The switching speed is therefore determined by the rate of collection (or resuspension) and the flow rate and path length within the system. The functionality of the system is based on the optical scattering and absorption of the dispersed particles, enabling both shading and enhanced solar-thermal energy uptake, which is, heating of the liquid. In the latter case, the carrier liquid is simultaneously used to distribute heat within the building or to further storage or conversion units. The general layout of the system is shown in Figure 3. In the following, these functions are demonstrated through experiments verified computationally, including the effects on room climate in a standard room simulation. Since shading alone is straightforward, this addresses primarily the energetic impact.

2.2. Modulation of Liquid Transparency and Shading

For reference, optical data were initially collected directly on suspensions with varying particle concentration and during bleaching (Figure 4). The opacity of the initial suspensions (Figure 4A) results from light scattering and absorption of the randomly distributed particles. Dynamic light scattering (DLS) confirmed average particle diameters <200 nm. The corresponding transmittance data are depicted in Figure 4B, indicating a variability within 100–8% across the considered range of particle concentrations for a geometric path length of 10 mm.

Using a magnet, particles can be drawn from the suspension, enhancing its optical transmittance. Figure 4C depicts a typical such example in which the particles from the fluid by applying a permanent magnet with a field strength of 0.4 T to the bottom of the cuvette, at a distance of 1.7 mm. In this case, a fraction of 93% of the initial transparency is recovered after about 4 min. Time-resolved studies of this bleaching effect were performed using a full-HD camera recording. Selected snapshots are shown in Figure 4C. The recorded images were then subjected to a grayscale analysis, taking the blank fluid as white reference. By convention, the bleaching time was defined as the time to reach 63.2% of the initial transmittance. Corresponding data are given in Figure 4D. A decrease is observed for the bleaching time with increasing particle concentration up to a level of 0.02 vol% (~45 s), beyond which no further improvement is seen.
2.3. Transmittance and Energy Uptake on Device Level

For evaluating the optical properties, the geometry of the present SPD is approximated as a side-by-side combination of two stacks A and B as shown in Figure 5A. These stacks are modeled as having finite thickness and semi-infinite length, and are evenly distributed over the device. Stack A corresponds to the part of the system composed of the capillary glass, a thin adhesive layer, and the cover glass. Stack B comprises the capillary glass, the fluidic layer, and the cover glass. The individual components are differentiated through their refractive index $n$ and their spectral absorption coefficient.

In Figure 5C, computer-generated data on spectral, angle-dependent reflectance and absorbance of the individual sections of SPD device are depicted, using a fluid with a particle concentration of 0.25 vol%. The employed glasses and the adhesive layer exhibit high transparency over the visible and near-IR spectral range so that the amount of absorbed energy
in stack A is negligible. In this case, the incoming radiation is fully transmitted or reflected at the layer interfaces. In stack B, significant absorbance is induced by the fluid layer. The imaginary part of the refractive index, \( k \), of stack B is estimated through 
\[
    k = \left( \alpha \cdot \lambda \right) / (4 \pi),
\]
with the absorption coefficient \( \alpha \) as obtained by spectrophotometry, and the wavelength \( \lambda \).

The reflectance and absorbance data were subsequently averaged over all incident angles between 0° and 90° relative to the surface normal and applied to a reference solar irradiance spectrum at air mass 1.5 to quantify the amount of reflected and absorbed solar energy on device level (Figure 5B). In the plots of Figure 5B, the difference between the red and the orange area depicts the amount of energy which is reflected back to the atmosphere. The blue region corresponds to the effective energy absorbed in stack B. Integrated data are summarized in Table 1. Since each of the stacks A and B occupies exactly one half of the system, the effective energy uptake of the system per area equals to one half of the values stated in Table 1.

**2.4. SPD Modulation and Shading**

Device operation under artificial illumination is illustrated in Figure 6, starting with the temperature difference \( \Delta T \) between inlet and outlet of a 300 × 210 mm² fluidic device for varying particle concentrations, a flow rate of 50 mL min⁻¹, and radiative load of 280 W m⁻². Very good agreement is found between experimental and computational data, confirming the applicability of the finite element model (FEM) model. Experiments were carried out under controlled conditions in such a way as to ensure that the inlet and surrounding temperature remains constant throughout the duration of the experiment. Therefore, the temperature increase which is recorded at the SPD outlet is exclusively due to irradiation. In Figure 6B, the harvested power is plotted, which allows quantifying the intrinsic harvesting efficiency at fixed flow rate and radiative flux density, but for varying particle concentration (Table 2).

| \( c \) [vol\%] | \( E_{\text{eff}, \text{stack B}} \) | \( E_{\text{eff}, \text{SPD}} \) |
|----------------|-----------------|----------------|
| 0.05           | 50.37%          | 25.19%         |
| 0.10           | 71.95%          | 35.98%         |
| 0.25           | 84.79%          | 42.40%         |

**Table 1.** Relative energy uptake \( E_{\text{eff}} \) in stack B and on SPD level for various nanoparticle concentrations \( c \). The estimated error on \( E_{\text{eff}} \) is ±2%.

| \( c \) [vol\%] | Harvested power [W, average] | Intrinsic harvesting efficiency |
|----------------|-----------------------------|-------------------------------|
| 0.05           | 4.10                        | 23.2%                         |
| 0.10           | 4.75                        | 26.9%                         |
| 0.25           | 5.87                        | 33.3%                         |

**Table 2.** Intrinsic harvesting efficiency for a 300 × 210 mm² fluidic window illuminated with a solar simulator (280 W m⁻²) for an inlet temperature of 20 °C and a flow rate of 50 mL min⁻¹. The estimated error on harvesting efficiency is ±2%.
Slight deviations between experimental data and the computational model, increasing with increasing particle concentration, are due to imprecise modeling of the optical properties of the loaded fluid, in particular, neglecting multiple scattering.

A second set of experiments is summarized in Figure 7. Here, the incoming radiative flux density was varied at constant flow rate (50 m min$^{-1}$) and particle concentration (0.25 vol%). Clearly, the amount of harvested energy increases with increasing radiative flux density. For the corresponding intrinsic harvesting efficiency, that is, the ratio between the amount of energy transferred to the system and the amount of energy which is harvested by the fluid, no significant variation was found around a value of (38.5 ± 1.3)%. That is, within the examined range of illumination intensity, there is a linear dependence of harvested power on illumination density.

2.5. Particle Collector-Suspender

Switching of the present SPD involves variation of the particle concentration in the fluid. To avoid contamination and to guarantee homogeneous flow through the whole system without introducing air bubbles, the separation process must take place in line, that is, without interrupting the fluid flow. A system for particle collection and resuspension is therefore implemented as depicted in Figure 3. The collector design was obtained through computational simulation of the particle–field interaction, from which magnet configuration and field strength were deduced for laboratory experiments. The final collector design is shown in Figure 8A. It includes a series of nine hose windings around 20 evenly spaced permanent magnets with field strengths of 1.26 T. The mounting brackets for the magnets can be automatically rotated for controlled particle attraction or release. For this system, upon switching to ON, the particle concentration at the outlet follows a decay function.

Figure 6. Computational prediction (left) and experimental quantification (right) of power harvested through a 300 × 210 mm$^2$ fluidic SPD under artificial illumination with a radiative flux density of 280 W m$^{-2}$, inlet temperature of 20 °C, and a flow rate of 50 mL min$^{-1}$. Data are shown for three particle concentrations. A) Temperature difference between the inlet and outlet of the system as a function of the time and B) harvested power.

Figure 7. Experimental quantification of the power harvested with a 300 × 210 mm$^2$ fluidic SPD under artificial illumination with variable radiative flux density for a flow rate of 50 mL min$^{-1}$ and a particle concentration of 0.25 vol%.

Figure 8. A) Collector design, B) Power harvested at different magnitudes of peak electric field, C) Energy harvesting efficiency, and D) harvestable power for different fluidic SPDs.
as shown in Figure 8B, subject to flow rate. Interestingly, the flow rate does not primarily affect the decay time. Instead, it affects the total number of particles which can possibly be collected while the liquid traverses the system. Collector parameterization and further optimization will hence need to be done with regard to the desired flow rate (determined by the thermal requirements of the system), magnet field strength (primarily determined through the use of permanent magnets or electromagnets), collector size, particle concentration in the fluid, and desired grade of shading. Tunable shading can be achieved through controlling the flow rate through the collector.

2.6. Use Cases and Room Model

In the envisioned application, the capillary glass element is part of a triple glazing, either on position 1|2 (facing outward, Figure 9A) or on position 5|6 (facing inward). On position 1|2, the device can be used as heat exchanger, reflecting the application described in the previous sections, where the outdoor environment is considered as a reservoir from which heat and solar energy is harvested. On position 5|6, the device acts as a heater (or cooler).

The first use case addresses a typical winter day, with an external temperature of −5 °C, an internal heat gain of 10 W m⁻², and an average specific radiation on the exterior wall of 100 W m⁻². Both capillary glass elements are supposed to be on position 5|6 and running with a flow rate of 20 L h⁻¹ m⁻² and a fluid temperature at the inlet of 23 °C. The air change rate is 0.5 h⁻¹. The steady-state temperatures at different positions of the room have been calculated when using a clear fluid and a particle-loaded fluid (absorption coefficient of 0.45). Obtained data are summarized in Table 3.

In this case, shading is disadvantageous for maintaining the interior temperature at a comfortable level.

The second use case addresses a typical transitional season day, with an outside temperature of 20 °C, zero internal heat gain, and a specific solar radiation on the external wall of 200 W m⁻². Both capillary glass elements are supposed to be on position 1|2 and running with a flow rate of 20 L h⁻¹ m⁻² and a fluid temperature at the inlet of 20 °C. The air change rate is 1 h⁻¹. The steady-state temperatures have been once again determined at different positions of the room when pumping a clear fluid or a particle-loaded fluid (absorption coefficient as above) though the SPD. Corresponding data are given in Table 4.

Here, particle-loading leads to a significant improvement of the room’s heat insulation as compared to the use of a transparent fluid (−4 °C decrease in room air temperature). This value compares to the previously reported performance of liquid-crystal-based IR reflectors,[36] although the mechanism of temperature control is very different in that the present fluid also acts as a thermal reservoir. In parallel to the temperature decrease, the energy harvested by the fluidic is substantially higher in this second use case as compared to the winter day.

3. Conclusions

In summary, we presented a switchable, ultrathin SPD for large-area integration with modern façades. The system is based on a fluidic window which is manufactured at low cost from a laminate of structured, rolled glass and a thin cover with high surface strength. As the key component of such a window, the laminate comprises an array of channels with cross sections in the range of mm² through which a fluid is circulating. Loading the circulating fluid with magnetic nanoparticles enables active shading and solar-thermal energy harvesting. The loading state, that is, the particle volume density can be controlled through remote switching in a particle collector-suspender device. This enables switching of the window’s optical properties, with typical switching times in the range of 1–2 min. In the shaded state, the device further enables solar-thermal energy harvesting. The typical harvesting efficiency reaches ~45% of the incoming solar power, which corresponds to a solar-thermal harvesting capacity in the range of 360 kWh a⁻¹ m⁻² for an average solar irradiance of 1000 W m⁻² during 800 h a⁻¹. The low thickness of the SPD of typically 4–6 mm allows for integration with standard double or triple glazings. Depending on application as a heater or heat exchanger, it can then replace the interior, the exterior, or both
of these glass panes in a regular insulation window. In comparison to alternative SPD concepts, this enables high flexibility and compatibility with established production lines. In addition, there is no need for further electrical contact, transparent conductive layers, or electrolytes. Use cases of indoor shading and heating are considered in a standard room model.

Table 3. Temperature at different positions of the room (winter day, heating).

| Description                           | Clear fluid | Particle-loaded fluid |
|---------------------------------------|-------------|-----------------------|
| Exterior wall inside surface temperature, $T_{ew}$ | 21.5 °C     | 19.8 °C               |
| Interior wall inside surface temperature, $T_{iw}$ | 22.4 °C     | 20.6 °C               |
| Floor surface temperature, $T_{floor}$   | 22.5 °C     | 20.7 °C               |
| Ceiling surface temperature, $T_{ceiling}$ | 22.3 °C     | 20.5 °C               |
| Fluidic device inside surface temperature, $T_{window}$ | 22.0 °C     | 21.3 °C               |
| Outlet temperature of the fluidic device | 22.0 °C     | 21.7 °C               |
| Room air temperature, $T_{i,air}$       | 22.0 °C     | 20.3 °C               |

Table 4. Temperatures at different positions of the room (transition day, heat exchanger).

| Description                           | Clear fluid | Particle-loaded fluid |
|---------------------------------------|-------------|-----------------------|
| Exterior wall inside surface temperature, $T_{ew}$ | 31.6 °C     | 27.8 °C               |
| Interior wall inside surface temperature, $T_{iw}$ | 31.8 °C     | 27.8 °C               |
| Floor surface temperature, $T_{floor}$   | 32.1 °C     | 28.0 °C               |
| Ceiling surface temperature, $T_{ceiling}$ | 31.6 °C     | 27.7 °C               |
| Fluidic device inside surface temperature, $T_{window}$ | 30.7 °C     | 27.2 °C               |
| Outlet temperature of the fluidic device | 20.8 °C     | 22.3 °C               |
| Room air temperature, $T_{i,air}$       | 30.8 °C     | 27.1 °C               |
4. Experimental Section

**Capillary Glass Elements:** For present study, device in two sizes were manufactured. Manufacture of capillary glass elements with a size of $300 \times 210 \text{ mm}^2$ as depicted in Figure 2B was described in detail in a previous study.[34]

For the manufacture of larger devices ($800 \times 600 \text{ mm}^2$, Figure 2C–E), capillaries with a cross section of about 3 mm$^2$ and an intercapillary distance of about 3 mm were embossed into conventional soda lime glass sheet (with maximum achievable size of $2000 \times 1275 \text{ mm}^2$) using an in-line rolling process implemented at the exit of a glass melting tank. Optical inspection was done to exclude significant warpage and material defects such as corks, bubbles, or knots. Bonding was performed through an ethylene-vinyl acetate film (Frieguard, Follenwerk Wolfen GmbH, Germany) which was applied at the interface between cover and capillary glass and cured at 130 °C and at 10 bar. After curing, the employed film is optically transparent across the visible spectral range with a refractive index of 1.48.[39] No defects such as liquid leakage or heterogeneity of bonding were observed throughout the experiments. For the cover sheet, a low-iron aluminosilicate glass with adapted coefficient of thermal expansion, $\alpha_{20-300} = 8.8 \times 10^{-6} \text{ K}^{-1}$ (AS87, Schott TGS) was used. The thermal conductivity $\Lambda_{25^\circ C}$ of the cover glass was 0.96 W m$^{-1}$ K$^{-1}$.

The obtained capillary glass pane was fit to a stainless steel distribution channel with a rectangular cross section of 100 mm$^2$ and a length of 600 mm to connect all capillaries. The capillary glass element was then incorporated into an insulating triple-glazing with PVC frame.

**Functional Fluid:** A noncorrosive water-glycol mixture (43 vol% Antifrogen L, Clariant Produkte GmbH, Germany) with low freezing point was used as dispersion medium for nanoscale magnetite particles. At 20 °C, this liquid has a density of 1.043 g cm$^{-3}$, a dynamic viscosity of 5 mPa s, and a refractive index of 1.382 across the visible spectral range. Its specific heat capacity at 20 °C is 2.5 kJ kg$^{-1}$ K$^{-1}$ and its thermal conductivity 0.21 W m$^{-1}$ K$^{-1}$. For particle loading, spherical iron(III) oxide particles (Fe$_3$O$_4$, Sigma-Aldrich, USA) with particle sizes ranging from 25 to 300 nm were put into silica cuvettes. Background corrections were performed for cuvette reflection.

**Table 5.** Optical and geometrical properties of stacks A and B for simulation of spectral reflectance and absorption on SPD level with wavelength $\lambda$ and the imaginary part of the refractive index, $k$, using a particle concentration of 0.05 vol%.

| Stack  | Refractive index | Thickness | Refractive index | Thickness |
|--------|-----------------|-----------|-----------------|-----------|
| Cover glass | 1.4605 + 0.0037i/$\lambda^2$ | 0.7 mm | 1.4605 + 0.0037i/$\lambda^2$ | 0.7 mm |
| Adhesive/loaded fluid | 1.506 | 5.0 μm | 1.382 + 1i| 1.0 mm |
| Capillary glass | 1.4605 + 0.0037i/$\lambda^2$ | 5.0 mm | 1.4605 + 0.0037i/$\lambda^2$ | 4.0 mm |

In this range, the employed glass module is practically fully transparent. The radiative flux was limited to 350 W m$^{-2}$ at a lamp-collector distance of 400 mm, according to ref. [38]. Besides Fresnel reflection from the glass surfaces and laminate interfaces, optical loss therefore determined solely through in contrast the particle concentration in the fluid.

**Computational Simulation:** For further parameterization and optimization, a 3D FEM was developed on software platform COMSOL Multiphysics v5.1. This model was used to determine the steady-state heat gain of the present SPD as a function of the particle concentration in the fluid, drawing from an earlier FEM model of the capillary glass.[34]

The different layers of the device as shown in Figure 5A were depicted as matrices which were multiplied to combine the effects of the adjacent layers and to find the transmissivity and reflectivity of the entire multiple-layer structure. Angle-dependent spectral reflectance and absorbance were thus obtained through the transfer matrix method[49] based on Fresnel equations, assuming a static fluid with a certain particle concentration. For this, the optical properties of the suspension were obtained from the transmission measurements, assuming that the non-transmitted part of the light is fully absorbed by the fluid. Further parameters used for the calculations are given in Table 5.

The particle collector-suspender design was similarly derived from computational simulation of the interaction between an ensemble of magnetite particles in a magnetic field. For this, the software platform COMSOL Multiphysics v5.1 was employed with the objective to identify a field geometry which enables efficient particle collection, and which can be implemented at low cost with the present SPD. This started by assuming a homogeneous distribution of spherical particles. On these, drag, diffusion, and magnetic forces were considered. The final design as depicted in Figure 8A involved an inner tube diameter of 12 mm, 20 rod-shaped magnets with a residual magnetic flux density of 1.26 T, a particle diameter of 1 μm (taking into account potential agglomeration), a particle density of 5000 kg m$^{-3}$, a fluid viscosity of 5.144 mPa s, a fluid density of 1.037 g cm$^{-3}$, and a magnetic permeability of the particles of 9. Fluid–particle interactions were initially neglected.

For testing the impact of the present SPD device on indoor climate, a computational room model was implemented. A room with dimensions 6 m × 4 m × 3 m was used as test environment. In the simulation, two capillary glass systems with an active surface of 2 m$^2$ were installed on the wall facing south. A specific heat gain of 10 W m$^{-2}$ was assumed, which corresponds to a typical heat gain value for small offices and compares with the harvesting power as determined experimentally for the present SPD. Furthermore, an air change rate (ACPH) of 0.5 was assumed. Further parameters are given in Table 6.

**Table 6.** Thermal transmittance of the room components.

| Component | Thermal transmittance [W m$^{-2}$ K$^{-1}$] |
|-----------|---------------------------------|
| Exterior wall | 0.28 |
| Interior wall | 0.23 |
| Floor | 0.35 |
| Ceiling | 0.35 |
| Fluidic device | 0.3 |

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Complementary information regarding the fluid motion and the heat transfer in the system is provided in an earlier publication.[34]

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

energy efficient buildings, energy harvesting, fluidic window, glass, magnetic properties, nanoparticles, smart windows, solar energy

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