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An artificial vasculature for adaptive thermal control of windows

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ABSTRACT

Windows are a major source of energy inefficiency in buildings. In addition, heating by thermal radiation reduces the efficiency of photovoltaic panels. To help reduce heating by solar absorption in both of these cases, we developed a thin, transparent, bio-inspired, convective cooling layer for building windows and solar panels that contains microvasculature with millimeter-scale, fluid-filled channels. The thin cooling layer is composed of optically clear silicone rubber with microchannels fabricated using microfluidic engineering principles. Infrared imaging was used to measure cooling rates as a function of flow rate and water temperature. In these experiments, flowing room temperature water at 2 mL/min reduced the average temperature of a model 10×10 cm^2 window by approximately 7–9 °C. An analytic steady-state heat transfer model was developed to augment the experiments and make more general estimates as functions of window size, channel geometry, flow rate, and water temperature. Thin cooling layers may be added to one or more panes in multi-pane windows or as thin film non-structural central layers. Lastly, the color, optical transparency and aesthetics of the windows could be modulated by flowing different fluids that differ in their scattering or absorption properties.

1. Introduction

A significant amount of thermal energy is transferred through building windows, both in the summer (heat gain) and winter (heat loss). In fact, windows typically represent the most significant factor responsible for building energy inefficiencies, due to this thermal loss or gain. Recent estimates suggest that windows account for about 40% of total building energy costs [1]. Yet windows are obviously a necessary feature of architecture, and in fact, architectural trends seem to show increasing usage of glass in building facades, which intensifies the problem further. Advanced fenestration systems have thus been developed to improve building efficiency, thermal comfort, and cost effectiveness [2–8]. Multi-pane windows, reflective glazing, low-emissivity (low-e) coatings, and variable tint are all technologies that have improved window and building efficiency [2–8]. Thin plastic films have been proposed as non-structural center panes to increase efficiency while maintaining overall window width, mass, and visual transmittance [9]. Flowing air or water between double panes was recently proposed to cool window panes and prevent window heat from being conducted to the building interior [10,11]. The design included air or water that naturally flowed upward due to buoyancy, or air/water pumped upward at higher speeds [10,11]. Since the thermal conductivity of water is much higher than that of air, the efficiencies of the water cooled designs were estimated to be higher [10,11].

In addition to building fenestration, semiconductor photovoltaic (PV) solar panels can suffer from absorptive heating, which reduces their energy generating efficiency by approximately 5% for each degree increase in operating temperature over 50 °C [12–14]. In fact, there are designs of hybrid photovoltaic–thermal (PV/T) solar collectors that collect thermal energy by convective cooling, generally using a series of pipes filled with flowing water behind the PV panels [15,16]. Therefore, cooling mechanisms for building windows can also benefit solar panel design.

In contrast to man-made thermal control systems, living organisms have evolved an entirely different and highly efficient mechanism to control temperature that is based on the design of internal vascular networks. For example, blood vessels dilate to increase blood flow close to the skin surface to increase convective

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heat transfer, whereas they constrict and limit flow when our skin is exposed to cold. In some birds, such as penguins, a counter-current flow mechanism is utilized within the vasculature to efficiently maintain a minimum temperature in the extremities [17]. Here we describe a new bio-inspired approach to thermal control for cooling (or heating) building window surfaces by incorporating transparent microfluidic heat exchange layers. The same approach may be used to control heat transfer across solar panel surfaces and improve the overall energy efficiency by reducing the operating temperature. Our results show that an artificial vascular network within a transparent layer, composed of channels on the micrometer to millimeter scale, and extending over the surface of a window, offers an additional and novel cooling mechanism for building windows and a new thermal control tool for building design.

2. Results

2.1. Temperature control in microfluidic windows

Experiments were conducted to explore the extent that an artificial vascular network lining a window surface can efficiently control the window temperature (or equivalently, the heat transfer across the window). We adapted microfluidic engineering techniques to fabricate optically clear, flexible elastomer sheets, containing rectangular channels, which were bonded to a glass window pane. Though single pane windows were used in our experiments for proof of concept, adding similar vasculature layers to one or more panes in a multi-pane window or engineering thin film non-structural central layers with vasculature are straightforward. The thin elastomer sheets were polydimethylsiloxane (PDMS) with channels having rectangular cross sections. Our two designs, called Diamond 1 and Diamond 2, had channel cross-sections (width by height) of 1 mm by 0.10 mm and 2 mm by 0.10 mm, respectively. The channels lined one side of the PDMS so that sealed networks of rectangular channels were formed when the PDMS layers were bonded to glass sheets (1/8″ thick, Fig. 1A). Flow entered an inlet on one side of a window and was distributed through a diamond network of channels (Fig. 1B). Importantly, although the channels were visible prior to infusion of liquid, they were not clearly visible when the channels were filled with water (Fig. 1B). The channels became almost entirely invisible if perfused with a fluid that more closely matched the refractive index of PDMS (1.43, data not shown).

Thermal infrared (IR) imaging enabled the thermal heat distribution of microvasculature networks to be visualized as a function of channel size, flow rate and initial water temperature. Prior to initiating fluid flow, the PDMS-glass composite window was heated by an incandescent light source (50 cm from the glass) to an initial temperature ranging from 35 to 40 °C. Water maintained at room temperature (RT, 21 °C) was then pumped through the microvascular channels at flow rates of 0.20, 2.0 and 10 mL/min. Changes in surface temperature were visualized using an IR camera as a function of the flow rate (Fig. 2A; darker colors indicate lower temperatures). The lowest flow rate (0.20 mL/min) had little effect on the overall window temperature, except around the inlet, while the high flow rate (10 mL/min) uniformly cooled the entire channel region whether the water flowing from the inlet was maintained at RT (Fig. 5) or 0 °C (Figs. 2, 5). Also, while the individual channels were initially visible, the cooled region spread to cover the entire microchannel network, reaching steady state within about 5 min for all flow rates.

To quantify the cooling effect, the window temperatures were averaged along a line extending between the inlet and outlet ports. This average window temperature was measured as a function of time for our Diamond 1 and 2 model windows described above at different flow rates (0.2, 2.0 and 10 mL/min). When the flow rate was higher than 0.20 mL/min, there was a significant drop in the average window temperature when water flowed through the channels at either 0 °C (Fig. 3A) or RT (Fig. 3B). As expected, the 0 °C flow at 10 mL/min caused the greatest cooling (to 8 °C, from the initial 35 °C), but even a modest flow of 2.0 mL/min of RT water was able to produce cooling from an average 37 and 39 °C to approximately 30 °C for the 1 and 2 mm wide channels of Diamond 1 and 2, respectively.

2.2. Analytic steady-state heat transfer model

To complement our experimental results, we developed an analytic steady-state heat transfer model to estimate the performance of a microfluidic thermally-controlled window and its dependence on scale, flow rates, water temperature, and material properties. When sunlight shines on the glass window, visible light passes through, but because the glass is effectively opaque to IR, radiative heating increases the temperature of the glass (Fig. 4). Heat diffuses through the glass, water-filled channel, and PDMS layers, while some energy is released back to the exterior and interior either as radiation or via air convection. Thus, when the exterior surface of the glass window is exposed to sunlight or heat, running cool water through the channels causes some of the energy to be absorbed and transported away, which prevents it from entering the room interior.

The steady-state analytic model was derived by an energy conservation argument that accounted for the thermal energy fluxes through the multiple layers of the window (glass, PDMS, water) and the thermal energy exchange with the exterior and interior air (for details, see SI). The model variables are the average cooling fluid temperature in the channel and the temperature along the exterior and interior sides of the window. The independent variable is the spatial coordinate in the direction of flow. Standard results from heat transfer [18] and fluid mechanics [19] were coupled with simplifying assumptions exploiting the following differences in length scales: the characteristic distances along the channel were much larger than the channel height and width; and the channel height was much smaller than the channel width and overall PDMS layer thickness. The steady-state model was developed in two steps. First, the preceding energy conservation argument was applied to the thermal fluxes across an infinitely wide window consisting of infinitely wide layers of glass and PDMS bounding an infinitely wide layer of water (Figs. 4,S1,S2). Second, the heat transfer across a finite window with evenly-distributed parallel channels was approximated by spatially averaging across and between the channels and applying a slight generalization of the steady-state model. The steady-state temperature of the cooling fluid in the channel, $T(x)$, and the steady-state temperature along the interior side of the window, $T_{IN}(x)$, both written in terms of the distance x along the channel from the inlet (for details, see SI), are

$$T(x) = T_\infty + (T_0 - T_\infty)\exp\left(-\frac{A\delta x}{Q}\right) \quad (1)$$

$$T_{IN}(x) = \frac{T(x) + B_p T_{room}}{1 + B_p} \quad (2)$$

where δ is the channel spacing (also defined for our diamond networks in Fig. S3), T_0 is the temperature of the water at the inlet, T_∞ is the static water temperature (i.e. when flow is off), T_{room} is RT, $B_p = 0.13$ is the Biot number characterizing the heat transfer through the PDMS layer, and A is a dimensional coefficient depending on the thermal properties of the PDMS, glass, and water. For water at 20 °C, $A = 1.94 \times 10^{-6}$ m/s (for details, see SI).