Thermally adaptive textiles (TATs) enable human subjects to attain thermal comfort without energy consumption, which can lead to enormous energy savings on heating, ventilation, and air conditioning (HVAC) in buildings. Herein, TAT structures which respond to the sweat and generate pores by opening an array of flap-shaped pores patterned on the fabric surface are proposed. A moisture-driven self-actuator for flap opening by constructing a bilayer consisting of a hygroscopic layer using polyethylene glycol and cellulose acetate, and a hydrophobic polymer using a polyester type polymer, is used and successfully demonstrated an essentially instant 4 °C apparent temperature cooling performance within one minute of sweat–humidity-initiated actuation while wearing TAT using a sweating skin simulated device.

1. Introduction

With increasing emphasis on sustainability, energy consumption for human thermal comfort is considered unavoidable, e.g., the energy utilization in heating, ventilation, and air conditioning (HVAC), which corresponds to ≈30% of energy consumption in buildings and homes in the USA. This huge energy use on buildings is economically equivalent to 16 billion dollars per year assuming an electricity rate of 10 cent kWh⁻¹.

An enormous saving of 320 million dollars per year is predicted by just turning the thermostat 1 °C up or down toward the ambient temperature in the buildings and homes across the USA. From the perspective of energy efficiency, localized heating and cooling of individual persons is much more efficient than heating or cooling of the whole room space or the whole building space. Therefore, numerous researches on smart clothes for human thermal comfort have been explored through optimization of heat transfer in textiles in an active or a passive way through radiation, convection, and conduction which enables energy savings in HVAC.

A physiological response of human skin utilizes a built-in adaptive thermoregulation mechanism which controls the mass transfer of water evaporation and associated evaporative cooling as the sensible heat from the surrounding air environment is absorbed and consumed as the latent heat necessary to evaporate water when the human body encounters an undesirable hot condition. We focused on this bio-inspired thermally adaptive benefit and used/expanded the function into a textile garment which can effectively adjust its air/humidity permeability by generating pores in the textile for adaptive mass transfer as needed. The thermally adaptive textile (TAT) that we propose can passively manage the latent heat transfer upon subject’s sweating without any electrically driven device or associated energy consumption (Figure 1A). The latent heat transfer management is an important mechanism to human physiology because the human body largely relies on the latent heat transfer, as sometimes over 50% of energy is emitted via high heat capacity of sweat vaporization from the skin.

The United States National Weather Service often forecasts and diagnoses heat discomfort in terms of the Heat Index (or Sultry Index). Human sweat and humidity accumulated under the garment substantially increase the Sultry Index as compared to the estimation of the human comfort based on the skin temperature alone. Furthermore, diversities from person-to-person physiological differences such as sex, age, and habitual characteristics based on climates from different residential areas do not allow a correct assessment of thermal comfort based on the skin temperature. Our TAT mechanism, which operates upon personal sweating, does not require any burden of tuning for the thermoregulation estimation of the garment involving individual physiology, whereas most other smart clothes need extra sensors or a calibration to fit the subject due to the temperature-only-derivative garments.
2. Results and Discussions

The steady-state model for thermal transfer on human body wearing TAT was solved based on the study by Steadman.\[16\] Two separate thermal transfer models with clothed (Figure 1B) and unclothed (Figure 1C) were built (Supporting Information), and the heat emission \(Q\) from human body is expressed by the clothed ratio \(\Phi\), the partial heat emission from clothed body part \(q_{\text{clothed}}\), and the partial heat emission from unclothed body part \(q_{\text{unclothed}}\).

\[
Q = \Phi \cdot q_{\text{clothed}} + \left(1 - \Phi\right) \cdot q_{\text{unclothed}}
\]  

(1)

Assuming that TAT has an adaptive property of changing \(\Phi\) in response to the humidity and temperature condition underneath the fabric \((P_s, T_s\) in Figure 1B), \(\Phi\) is addressed to meet the following equation

\[
\Phi = \begin{cases} 
1, & \text{when } f(P_s, T_s) < A \\
1 - \alpha, & \text{when } f(P_s, T_s) \geq A 
\end{cases}
\]

(2)

where \(\alpha\) is the coverage ratio of textile-extracting flap area (the area corresponding to the opened flaps) on human body, and \(A\) is the criteria that the human subject feels uncomfortable indicating a need to operate the TAT for the cooling performance. The function \(f\) that we suggest is based on the absolute humidity \(\text{AH}\), which can be easily estimated from the temperature and relative humidity \(\text{RH}\), and is useful for the actual moisture criteria that can be used for designing effective materials. Figure 1D shows the coverage ratio of textiles needed to meet human thermal comfort with regards to the ambient temperature and the RH (see Supporting Information).

Figure S1, Supporting Information, shows the AH\(\) above the skin \((P_s\) in Figure 1B) while wearing the normal clothes to fulfill the thermal comfort. The desirable AH\(\) on the skin at 50% RH and 20–30 °C ambient temperature range is 16–21 g m\(^{-3}\), which indicates that TAT should respond at the AH above 20 g m\(^{-3}\) to initiate a decrease in the coverage ratio of \(\Phi\), and to increase the mass transfer in balance with the heat emission. If the changeable coverage ratio of textiles is 0.5 with half of the textile area having flaps, the simulation shows that the cooling effect of wearing a TAT can cope with 5 °C of the ambient temperature change to maintain the desirable human thermal comfort.

There are many moisture-driven actuators using hygroscopic materials such as bacterial spores,\[17\] conductive polymer,\[18,19\] and biomaterials.\[20\] These actuators show the promising performance of mechanical transformation in a humid condition; however, the material itself is not suitable for textile materials due to the inherent difficulty in handling biomaterials and/or ionic materials, and their relatively high cost is also a barrier to industrial applications in the textile field. We also suggested Nafion as moisture-driven actuators for smart textiles.\[21\]

The polymer network structure of Nafion is noted because of its hydrophobic based matrix with hygroscopic property of sulfonic acid within, which can show stable performance of swelling upon humidity increase. However, it is expensive and releases hydrogen or metal ions which can damage human skin, making Nafion unsuitable for fabric-related applications.

Therefore, we have designed alternative materials in consideration of safety for human skin, much lower in cost,
and textile-friendly material characteristics, which will perform the desired humidity-controlling functions in textile form (see the cost analysis in Supporting Information). One successful example of such desirable functional materials is a combination of polyethylene glycol (PEG) and cellulose acetate (CA), with an internal structure of PEG dispersed in the CA material. PEG is an extremely hydrophilic material, with a highly undesirable, sticky feeling on the skin, which is not really suitable as a textile material. We thus used CA as the host material to harness the hydrophilic material while the sticky behavior can be mostly prevented. CA is also one of the well-known textile materials frequently used in the industry. Mixture of ethanol and acetone having an intermediate surface tension with polymers was chosen as the solvent for the purpose of dispersing PEG in CA. For a desirable moderate degree of phase separation of PEG in CA matrix, a similar level molecular weight of PEG (Mn20 000) was chosen as compared to CA (Mn 50 000) based on the Flory–Huggins mixing theory. The hygroscopic property of the polymers was measured with quartz crystal microbalance (QCM) in a customized humidity chamber which mimicked a human skin evaporation system (Figure S2A). Then, 50 μm sized holes were punched in a polyethylene terephthalate (PET) film (Figure S2B, Supporting Information), the size of which is almost the same as that of human sweat glands with a density of 150 holes cm⁻², the same number of sweat glands in the abdomen. The humidity is maintained at 60–70% RH, whereas the temperature was controlled in the range of 24–30 °C in the humidity chamber by heating the hot plate with sufficient amount of water placed underneath the pore-punched PET film (Figure S2A, Supporting Information). This humidity and temperature profile corresponds to the 15–21 g m⁻³ range in AH. Four polymer samples were prepared as follows: 100% pure CA, 5% (in wt%) PEG in CA, 10% PEG in CA, and 15% PEG in CA in weight percent. The hygroscopic property was measured in the humidity chamber under the condition of 16–21 g m⁻³ AH.

As the PEG content in CA is increased, the polymer absorbs more water from the vapor as shown in Figure 2B due to the enhanced hygroscopic property of the composite structure having more PEG (see the Experimental Section in the Supporting Information). For the actuator fabrication, the composite material of 10% PEG in CA was chosen since it has been found that 15% PEG in CA noticeably reduces the tensile strength of the film. Considering that the density of polymer (1.27 g m⁻³) is not substantially different from that of water (1.0 g m⁻³), the volume swelling of 10% PEG-in-CA is expected to be ≈1% volume change (g m⁻³)⁻¹ in response to the change in AH. The AH of 16–21 g m⁻³ corresponds to the range of humidity from 40–50% RH to 50–70% RH in the temperature range of 30–37 °C (Figure S2C, Supporting Information), which is similar to the temperature gradient and the humidity level between the clothing and human skin (37 °C), and thus, at the target AH of 16–21 g m⁻³, the actuator should respond to open the flaps.

We have constructed this moisture-driven actuator as a bilayer structure pairing the hydrophobic layer, PET (the most common thermoplastic polymer resin of the polyester), with the hygroscopic polymer layer (composed of 90% CA and 10% PEG). As the hygroscopic layer expands by absorbing moisture, the layer bends toward the hydrophobic layer side since the hydrophobic layer does not absorb water and expand in the humid condition, which creates a bending stress. The bending behavior of the polymeric bilayer was simulated by evaluating the dislocation (h) of the edge of the film from the flat state (Figure 3B). The h is expressed by the following equation(22)

$$h = \frac{2}{k\left(\frac{1}{\tan\theta} + 1\right)}$$

(3)

$$k = \frac{6E_1E_2(h_1 + h_2)h_2\mu A \cdot \Delta AH}{E_1h_1^4 + 4E_1E_2h_1^2h_2 + 6E_1E_2h_2^3 + \mu E_2h_2^4}$$

(4)

where $E_1$ and $h_1$ are the Young's modulus and the thickness of the hygroscopic layer and $E_2$ and $h_2$ are for the hydrophobic layer, l is the length of the sample, A is the 2D hygroscopic expansion of the hygroscopic layer in response to the change in AH (ΔAH). The thickness of each layer was 20 μm for the PET layer and 20 μm for the CA layer, which were optimized numerically to maximize the shape transformation based on the double-beam theory. The bar-shape film (Figure 3A) and

Figure 2. Characterization of the hygroscopic property of the polymer. A) Schematic illustration of the measurement setup. B) Hygroscopicity measured by QCM in response to the change in AH for composites of (PEG 0% + CA 100%), (PEG 5% + CA 95%), (PEG 10% + CA 90%), and (PEG 15% + CA 85%).
the TAT by laminating bar-shape moisture-drive actuator underneath the flap (Figure 3B) actuates and bends by increasing AH from 12 g m$^{-3}$ (25°C, 50% RH) to 18 g m$^{-3}$ (27°C, 70% RH).

Other flap shapes such as triangular or circular geometries were also tried for moisture-driven actuators having similarly laminated structures. (Figure S3 and Figure S4, Supporting Information). All the actuators performed well and showed the successful shape transformation at the higher humidity; however, TAT with circle and triangle showed incomplete flap-opening behaviors partly due to the reduced average
length-to-width aspect ratio, with which the expansion of hygroscopic layer was constrained lengthwise to contribute to the shape transformation (Figure S4, Supporting Information). The bar shape with a moderate aspect ratio was thus fabricated and developed into TAT structure using some commonly used fabrics by seamless adhesion between layers (Figure S5, Supporting Information). Three textile materials including knitted and woven structures, with cotton or polyester type fabric, were utilized for the TAT fabrications (Figure 3C). All the TATs so fabricated showed very similar degrees of flap-opening behavior (Movie S1) at the higher humidity (18 g m\(^{-3}\) AH) although they have varied elastic modulus and thickness values (Table S1, Supporting Information).

To more quantitatively investigate the flap-opening behavior in TAT, the height at the edge (end) of the opened flap from the flat state was measured at various levels of humidity and temperature. Such variations in temperature and humidity conditions were provided in the skin-mimicked humidity chamber to simulate the fabric-on-human-skin condition. For the colder temperature regime, an additional skin-mimicked humidity chamber using a double jacket holder connected to a chiller was utilized to measure the humidity response of the samples. (Figure S6, Supporting Information). Three temperature and humidity regimes were tested as follows: 1) high humidity conditions (25–40 °C, 50–90% RH) (Figure 4A), 2) relatively drier conditions (24–35 °C, 51–29% RH) (Figure 4B), and 3) colder temperature conditions (10–33 °C, 60–65% RH) (Figure 4C), for each of which the flap heights were plotted with regards to the temperature and the humidity.

The resulting flap behavior in drier conditions (Figure 4B) with the AH held constant demonstrate that the temperature change alone does not affect the flap translocation, with practically no flap opening seen. As converted into AH and plotted with the height of flaps as shown in Figure 4D, the flap starts to open at a level of 10–20 g m\(^{-3}\) AH, and the degree of flap opening begins to saturate at the AH level of 30–35 g m\(^{-3}\), which almost agrees with the simulation results (Figure S7, Supporting Information) which indicate a 1.8 cm height translocation of the flap (2.5 cm length) by the AH change of 30 g m\(^{-3}\). This is based on the assumption that the flap length expansion (by humidity absorption) per ΔAH is 0.3% (g m\(^{-3}\)) which is obtained from 1% volume change (g m\(^{-3}\)) of the real material.

![Figure 4. Flap-opening behaviors in response to the AH change. A) Height of flaps from the base line (horizontally flat status) in response to a broad range of RH conditions and temperatures (25–40 °C, 50%-90% RH). B) Height of flaps from the base line in response to a relatively low AH (24–35 °C, 51%-29% RH). C) Height of flaps from the base line in response to cold conditions but with a steady RH (10–33 °C, 60%-65% RH). D) Summarized outcome from the data in (A–D), with the maximum flap height plotted with respect to the AH.](image-url)
Figure 5. Simulated skin thermal transfer measurement under TAT. A) Schematic illustration of the measurement setup. The thermocouple for the “simulated skin” measurement is placed ≈2.5 cm below the fabric sample over the 3 mm thickness aluminum plate, together with a wet paper towel to simulate a person sweating upon feeling hot. The heat sheet was attached below the aluminum plate and another set of thermocouple and humidity sensor was placed underneath the fabric sample. The measurement setup is placed in the large chamber to ensure the constant ambient condition such as the same convection and radiation for each set of experiments. B) RH and temperature (T) underneath the fabric samples (blue: TAT, red: normal textile), AH converted from RH and temperature, and ST which was collected from the “simulated skin.” Then, 100 μl of water droplet was supplied onto the dried tissue at 50 s. C) Temperature difference (ΔT) and ST difference (ΔST) between TAT and normal textile. D) IR images of closed flaps and opened flaps on TAT. E) ATs over the simulated skin under TAT versus normal textile on flap opening, and the difference of ATs (ΔAT) between TAT and normal textile.
volume expansion (Figure 4D). It is noticeable that the flap initiates the operation of opening relatively fast within a few seconds in a humid environment (although it takes a few minutes to reach the saturated degree of opening) so as to recover the stress equilibrium between the elastically stressed hygroscopic layer (by volume expansion) and the attached hydrophobic layer.

The thermoregulation function of TAT was investigated by using the simulated skin measurement in lieu of human subject testing. Figure 5A shows the measurement setup which is composed of an insulation container with inside a heat sheet, aluminum sheet, and tissue placed in order. The aluminum sheet provides a uniform thermal distribution on the surface and tissue is utilized to distribute the moisture quickly on the surface, which is supplied by the pipette. The thermal power generation by the heat sheet was set to 50 W m\(^{-2}\) by supplying 5.2 V to the heat sheet (Figure S8, Supporting Information) and the surface temperature (ST) was 38 °C which is similar to human skin temperature. The thermal emission of 50 W m\(^{-2}\) is equivalent to the metabolic rate of human normal activity such as a subject sitting in a chair or walking around the room.\(^{[23]}\)

After placing a textile sample over the simulated-skin measurement tool, a thermocouple was placed on the surface and an additional thermocouple and humidity sensor were placed underneath the textile to measure the ST, and the temperature (T) and the humidity (RH) between the surface and the textile sample. Then, 100 μl of water was supplied on the dried tissue (surface area is 17.4 cm\(^2\)) in the insulation box, and this amount of water corresponds to the physiological perspiration of 3 mL m\(^{-2}\) min\(^{-1}\) emitted from the person walking around the room.\(^{[23]}\) Figure 5B shows RH, T, AH (which is converted with RH and T), and ST measured with the normal textile (knitted, PE 60%, rayon 39%, and spandex 1%) and TAT made with the same textile (flap pattern is 2.5 cm in length and 1.3 cm in width), which has the coverage ratio of flap area to the textile is 0.26. The ambient temperature was 24 °C and the ambient humidity was 60% RH, which is a moderate weather condition with 13 g m\(^{-3}\) AH. Although RH underneath the normal textile exceeds 70% RH, TAT manages less than 70% RH and drops T significantly compared to the normal textile (Figure 5B). The cooling effect of maximum 1.5 °C of T and 1 °C of ST were obtained with the TAT (Figure 5C). A noticeable cooling of 1 °C compared to a normal textile was obtained within 1 min after the initiation of flap opening. Infrared (IR) images before and after flap opening are shown in Figure 5D, which demonstrates the accumulated heat under the textile was emitted through the pore generated by flap opening (Movie S2, Supporting Information).

To evaluate the sensed thermal condition including the humidity effect, the well-known concept of “apparent temperature” (AT) was used along with temperature and is shown in Figure 5E. Significant drop in AT were observed with TAT, which improves the thermal condition to less than 35 °C AT, the value over which a person feels a strong thermal discomfort. Normal textiles stay a much longer time in the strong discomfort regime (35–40 °C AT) than TAT and the maximum 6 °C cooling (immediate 3 °C AT cooling effect after flap opening) was obtained with TAT compared to the normal textile (Figure 5E). As a result, TAT provides the rapid recovery of a sweating body and maintains the body’s thermal comfort, which the normal textile cannot achieve.

To evaluate the repeatability of the flap-opening behavior, multiple bending of the flap was performed, with the humidity cycling done indirectly utilizing cooling as a means of introducing humidity change. Recall that it was experimentally demonstrated that temperature change alone from 22 to 32 °C did not cause the flap to open at all (Figure 4B). By this method, the moisture was supplied every 30 min over five repetition (Figure 6). The constant flap opening and associated cooling performances in temperature, RH underneath TAT, and the skin temperature were observed with regards to the ambient

![Figure 6](image-url)
condition (Figure 6B). Flap-opening behavior was further tested 100 times with a robotic arm customized to move back and forth to turn humidity exposure on and off. This allowed a placement of the textile sample into the humid environment (32 °C, 50% RH) versus the ambient condition (22 °C, 45% RH) 100 times automatically (Figure S9, Supporting Information). The flap opens regularly for all 100 exposures reproducibly without failures (Figure S10, Supporting Information). The repeatability test should be extended to further resting to fulfill the real applications in the future. The basic properties of our TAT fabric met some of the key performance criteria in the fabric industry such as wear resistance, wicking property, and breathability as these properties were found to remain essentially as in the original fabric, especially since the humidity-responsive actuators can be somewhat infrequently added as an option to trade the speed of flap-open-induced cooling with the improved matrix fabric properties and more inconspicuousness. Our humidity responsive TAT structure can be useful for other types of layer materials requiring a low breathability such as in membranes and nonwoven textiles in which a substantially enhanced cooling performance is also achieved.

The flaps, if made reasonably large, are certainly visible with a possible issue of aesthetically less pleasing appearance. Designing to accommodate flaps in clothes in a fashionable way might overcome such an issue. For example, the flaps can be made smaller such as in a millimeter scale, they can be designed to curve toward inward instead of outward to be less conspicuous, or the flaps can be incorporated as a part of some clothing design features to be less visible, e.g., in a heart shape, mountain shape, and so forth. We are expanding our research concepts into humidity controllable membranes, which can manage and optimize humidity in a given space, and which can be applied as controllable materials for buildings, appliances (e.g., as self-adjustable crisper units in refrigerators that need to maintain certain humidity levels to keep vegetables fresh), greenhouses, and so forth for humans as well as for plants.

3. Conclusion

We developed the smart fabric which can self-adjust its air permeability by opening the flaps embedded in the textile in response to the wearer’s sweating degree. The fabric is designed to initiate the flap-opening operation at 20 g m⁻³ AH, which is the AH that is formulated by sweating people, and results in 4 °C of an immediate cooling in AT. The adaptive passive cooling performance of our humidity-responsive smart layer structure can be useful for other applications such as buildings, greenhouses, refrigerators, or other confined spaces that require convenient means of humidity control. All data needed to evaluate the conclusions in the article are present in the article and/or in the Supporting Information.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

G.K., Y.Z., and S.J. conceived the project idea and G.K. designed and conducted the experiments. C.G. and K.P. assisted the experiments. G.K. and S.J. wrote the article. S.J. supervised the research and participated in the discussions of the results and interpretations.

Keywords

bilayer actuators, evaporative cooling, hygroscopic polymers, smart textiles, thermal comfort

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