Analytical transient phase change heat transfer model of wearable electronics with a thermal protection substrate*

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Abstract As thermal protection substrates for wearable electronics, functional soft composites made of polymer materials embedded with phase change materials and metal layers demonstrate unique capabilities for the thermal protection of human skin. Here, we develop an analytical transient phase change heat transfer model to investigate the thermal performance of a wearable electronic device with a thermal protection substrate. The model is validated by experiments and the finite element analysis (FEA). The effects of the substrate structure size and heat source power input on the temperature management efficiency are investigated systematically and comprehensively. The results show that the objective of thermal management for wearable electronics is achieved by the following thermal protection mechanism. The metal thin film helps to dissipate heat along the in-plane direction by reconfiguring the direction of heat flow, while the phase change material assimilates excessive heat. These results will not only promote the fundamental understanding of the thermal properties of wearable electronics incorporating thermal protection substrates, but also facilitate the rational design of thermal protection substrates for wearable electronics.

Key words wearable electronics, functional composite, theoretical heat transfer analysis, thermal management

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1 Introduction

Recent advances in mechanical design^[1–4] and advanced manufacturing techniques^[5–8] have enabled the development of high-performance wearable electronics by integrating inorganic functional materials onto soft polymer substrates. The ability of wearable electronics to function under complex deformations ensures their close contact with human skin in digital healthcare applications^[9] for the continuous monitoring of vital signs. These signs include the skin humidity^[10], the epidermis temperature^[11–12], the blood flow rate and volume^[13–14], the peripheral capillary oxygen saturation^[15–17], and the mechanical properties and response of skin^[18–19]. Wearable electronics also allow noninvasive measurements of glucose levels^[20–21], brain electrophysiological signals^[22–23], and electrocardiography signals (ECG)^[24] for early diagnosis. Because of the weak thermal dissipation performance of the flexible polymer substrate, the functional components in wearable electronics may cause undesirable heat accumulation on skin and induce thermal damage in practical applications. To improve the heat dissipation of the substrate and thus reduce the adverse thermal effects, researchers have proposed several strategies such as increasing the effective thermal conductivity of the substrate^[25–26], manipulating the heat flow in the substrate^[27–28], and enhancing the heat absorption ability of the substrate^[29].

Recently, an alternative strategy combining the heat flux manipulation and effective excessive heat assimilation by a functional soft composite was reported^[30]. This novel functional composite is composed of a paraffin phase change material layer below the Cu metal foil layer with both layers encapsulated by flexible polymer materials. Figure 1 schematically illustrates a flexible wearable heater composed of a circular ultra-soft gold heating electrode and a thermal protection substrate integrated with the electrode. The experimental results show that, compared with a homogeneous polymer substrate, the temperature increment can be significantly controlled by the novel substrate, and the cooling efficiency can reach more than 85% under appropriate conditions. A full understanding of the physics associated with the heat transfer in the thermal protection substrate is critical for further optimization.

Although the underlying thermal management mechanism of heat flux direction reconfiguration and excess heat assimilation via the phase change process has been investigated both experimentally and numerically^[30], an analytical model is critically required to better understand the thermal behavior of the thermal protection substrate and offer guidance for the optimal design of the substrate.

The purpose of this paper is to establish an analytical transient phase change heat transfer model validated by experiments and the finite element analysis (FEA) to investigate the heat transfer behavior of a flexible electronic device incorporating the thermal protection substrate. The effects of the substrate structure size and heat source power input on the maximum temperature reduction are investigated systematically and comprehensively. The contents of this paper are organized as follows. The model for the wearable electronics device is presented in Section 2, and that for the wearable electronics device/skin system is presented in Section 3. Section 4 concludes this paper.

2 Thermal modeling of the wearable electronics device with a thermal protection substrate

Figure 1(a) schematically illustrates the axisymmetric circular ultra-soft heater with a thermal protection substrate modelled analytically. A cylindrical coordinate system is used in which the origin is located at the center of the bottom of the substrate, the r axis points from left to right, and the z axis points from the bottom to the top. The interfaces in the system are located at z_1 , z_2 , z_3 , and z_4 . The radii of the heater, thin Cu film, paraffin, and

Fig. 1 (a) Schematic diagram of a flexible wearable electronic device. (b) Structural composition of the thermal protection substrate (color online)

polydimethylsiloxane (PDMS) are R_h , R_1 , and R_2 , respectively. The heater is thin (about $10\mu\text{m}$) and can be modeled as a planar heat source with an input power (or heat generation power) denoted by Q .

An enthalpy-based model^[31] is adopted to model the heat transfer in the paraffin phase change material. Depending on the temperature, the paraffin can be in a solid phase, a liquid phase, or a mixture of the solid and liquid phases. The relationship between the temperature and enthalpy can be expressed as

$$H = \begin{cases} c_s T, & T < T_s, \\ c_s T + \frac{T - T_s}{T_1 - T_s}, & T_1 \leq T \leq T_s, \\ c_l (T - T_1) + c_s T_1 + L, & T > T_1, \end{cases} \quad (1)$$

where T_s is the solidus temperature, T_1 is the liquidus temperature, L is the latent heat of the phase transition, c_s is the solid phase specific heat capacity, and c_l is the liquid phase specific heat capacity of paraffin.

The heat transfer equation within the paraffin region ($r < R_1$ and $z_1 < z < z_2$) is

$$\rho_{\text{paraffin}} \frac{\partial H}{\partial t} = k_{\text{paraffin}} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right). \quad (2)$$

ρ_{paraffin} and k_{paraffin} are respectively the density and thermal conductivity of paraffin, which are given by

$$\rho_{\text{paraffin}} = \begin{cases} \rho_s, & T < T_s, \\ \rho_s + \frac{\rho_l - \rho_s}{T_1 - T_s} (T - T_s), & T_1 \leq T \leq T_s, \\ \rho_l, & T > T_1, \end{cases} \quad (3)$$

and

$$k_{\text{paraffin}} = \begin{cases} k_s, & T < T_s, \\ k_s + \frac{k_l - k_s}{T_1 - T_s} (T - T_s), & T_1 \leq T \leq T_s, \\ k_l, & T > T_1. \end{cases} \quad (4)$$

Here, ρ represents the density, and k represents the thermal conductivity. The subscript s denotes the solid phase, and l denotes the liquid phase.

The heat transfer equation in the Cu film region ($r < R_1$ and $z_2 < z < z_3$) is

$$\rho_{\text{Cu}} c_{\text{Cu}} \frac{\partial T}{\partial t} = k_{\text{Cu}} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right), \quad (5)$$

where ρ_{Cu} , c_{Cu} , and k_{Cu} are respectively the density, specific heat capacity, and thermal conductivity of the Cu film.

The heat transfer equation in the PDMS region ($R_1 < r < R_2$ or $z < z_1$ or $z_3 < z < z_4$) takes the similar form of

$$\rho_{\text{PDMS}} c_{\text{PDMS}} \frac{\partial T}{\partial t} = k_{\text{PDMS}} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right), \quad (6)$$

where ρ_{PDMS} , c_{PDMS} , and k_{PDMS} are respectively the density, specific heat capacity, and thermal conductivity of PDMS.

The interface continuity conditions include the continuity of the temperature and the heat flux. At the paraffin/PDMS interface, the temperature satisfies

$$T|_{z=z_1^-} = T|_{z=z_1^+}, \quad -k_{\text{PDMS}} \frac{\partial T}{\partial z} \Big|_{z=z_1^-} = -k_{\text{paraffin}} \frac{\partial T}{\partial z} \Big|_{z=z_1^+} \quad (7)$$

with $0 < r < R_1$ and

$$T|_{r=R_1^+} = T|_{r=R_1^-}, \quad -k_{\text{PDMS}} \frac{\partial T}{\partial r} \Big|_{r=R_1^+} = -k_{\text{paraffin}} \frac{\partial T}{\partial r} \Big|_{r=R_1^-} \quad (8)$$

with $z_1 < z < z_2$. At the paraffin/Cu interface, the temperature satisfies

$$T|_{z=z_2^+} = T|_{z=z_2^-}, \quad -k_{\text{paraffin}} \frac{\partial T}{\partial z} \Big|_{z=z_2^+} = -k_{\text{Cu}} \frac{\partial T}{\partial z} \Big|_{z=z_2^-} \quad (9)$$

with $0 < r < R_1$. At the Cu/PDMS interface, the temperature satisfies

$$T|_{z=z_3^+} = T|_{z=z_3^-}, \quad -k_{\text{Cu}} \frac{\partial T}{\partial z} \Big|_{z=z_3^+} = -k_{\text{PDMS}} \frac{\partial T}{\partial z} \Big|_{z=z_3^-} \quad (10)$$

with $0 < r < R_1$ and

$$T|_{r=R_1^+} = T|_{r=R_1^-}, \quad -k_{\text{Cu}} \frac{\partial T}{\partial r} \Big|_{r=R_1^+} = -k_{\text{PDMS}} \frac{\partial T}{\partial r} \Big|_{r=R_1^-} \quad (11)$$

with $z_2 < z < z_3$. The natural convection boundaries give

$$\begin{cases} -k_{\text{PDMS}} \frac{\partial T}{\partial z} \Big|_{z=0} = -h(T - T_a)|_{z=0}, \\ -k_{\text{PDMS}} \frac{\partial T}{\partial z} \Big|_{z=z_4} = -h(T - T_a)|_{z=z_4} - Q \times \text{heaviside}(r(R_h - r)), \\ -k_{\text{PDMS}} \frac{\partial T}{\partial r} \Big|_{r=R_2} = -h(T - T_a)|_{r=R_2}. \end{cases} \quad (12)$$

The axisymmetric boundary gives

$$-k_i \frac{\partial T}{\partial r} \Big|_{r=0} = 0 \quad (13)$$

with i denoting paraffin, Cu, or PDMS.

Solving the heat transfer equations (2), (5), and (6) with the interfacial and boundary conditions in Eqs. (7)–(13) gives the temperature in the system. Because of the complexity of the problem, the finite difference method is employed to solve for the distribution of the temperature field. The geometrical and loading parameters obtained from the experiments are taken to verify the analytical model. The radii of the circular ultra-soft heater, Cu film layer, paraffin layer,

and substrate are 3.5 mm, 7.5 mm, 7.5 mm, and 16 mm, respectively, which give $R_h = 3.5$ mm, $R_1 = 7.5$ mm, and $R_2 = 16$ mm. The paraffin layer is located in the medial position of the cross section of the thermal protection substrate. The thicknesses of the thermal protection substrate, paraffin, and Cu film are 3 mm, 2 mm, and 50 μm , respectively, which give $z_1 = 0.5$ mm, $z_2 = 2.5$ mm, $z_3 = 2.55$ mm, and $z_4 = 3$ mm. The input power of $Q = 661.5$ mW, is calculated based on the input current of 70 mA and heater resistance of 135 Ω using Joule's heating law. The coefficient of natural convection is $12 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ ^[32]. The ambient temperature $T_a = 26^\circ\text{C}$. The material parameters of Cu^[33] are $\rho_{\text{Cu}} = 8.9 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$, $c_{\text{Cu}} = 386 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, and $k_{\text{Cu}} = 394 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. The parameters for PDMS^[34] are $\rho_{\text{PDMS}} = 0.97 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$, $c_{\text{PDMS}} = 1460 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, and $k_{\text{PDMS}} = 0.15 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. Those of paraffin^[35–38] are $\rho_s = 9.16 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$, $c_s = 1920 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, and $k_s = 0.12 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ in the solid phase; $\rho_l = 7.9 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$, $c_l = 3260 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, and $k_l = 0.089 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ in the liquid phase; $T_s = 56^\circ\text{C}$, $T_l = 58^\circ\text{C}$, and $L = 256 \text{ kJ} \cdot \text{kg}^{-1}$.

Fig. 2 (a) Schematic diagram of the simplified axisymmetric model for the phase change heat transfer structure. (b) FEA, analytical, and experimental results of maximum temperature at the bottom surfaces of the PDMS and thermal protection substrates (substrate thickness: 3 mm and heating time: 70 s). (c) Evolution of the maximum temperature with time on the substrate bottom (heating time: 1500 s and substrate thickness: 3 mm) (color online)

When the wearable electronics device is placed on the skin, the highest temperature on the skin is located at the interface between the device and the skin. The location of this point is shown in Fig. 1(b) with a blue dot. This maximum temperature is used to illustrate the performance of the thermal protection substrate. Figure 2(b) shows the evolution of the maximum temperature at the substrate bottom with time over a heating time of 70 s for both the PDMS and the thermal protection substrate. The maximum temperature increases to the peak value during the heating duration and then decreases to the ambient temperature with a time delay after the heating has stopped due to the thermal conduction from the heater on the top to the substrate bottom. The maximum temperature occurs at 76 s with a time delay of 6 s for the PDMS substrate, while the peak temperature occurs at 90 s with a time delay of 20 s for the thermal protection substrate. Moreover, compared with the PDMS substrate, the maximum temperature of the thermal protection substrate is significantly reduced by 76%

from 105 °C to 43 °C. To validate the accuracy of the analytical model, the results from the experiments (solid dot) and the FEA (open triangle) are also shown in Fig. 2(b). The DC3D10 element type is used in the FEA model. The total number of the elements exceeds 61 000 with the size of the elements ranging from 0.05 mm to 2 mm. The convergence of the FEA model is verified by reducing the element size by an order of magnitude. The details of the experiments and the FEA can be found in Shi et al.^[30]. The analytical, experimental, and finite element results agree well with one another. This verifies the correctness and accuracy of the analytical method.

To further investigate the underlying thermal protection mechanism of the thermal protection substrate, the evolution of the maximum temperature with time on the substrate bottom over a heating time of 1500 s is shown in Fig. 2(c). Compared with the simple monotonically increasing response of the PDMS substrate, the thermal protection substrate exhibits a much more complicated four-stage thermal behavior. At stage I, the temperature increases monotonically but at a much lower increase rate due to the modification of the heat flux by the high-thermal conductivity Cu foil layer. At this stage, the temperature of the paraffin has not yet reached the paraffin phase transition point. At stage II, the temperature is relatively constant because of the paraffin phase change due to the absorption of excessive heat energy. At stage III, the temperature begins to rise again until the steady-state temperature after the phase transition is fully completed. At stage IV, the temperature remains in the

Fig. 3 The variation of the maximum temperature at the bottom surfaces of the (a) PDMS and (b) thermal protection substrates with the input power and heating duration time. (c) The variation of the temperature reduction with the input power and heating duration time (substrate thickness: 2 mm) (color online)

steady state. These results clearly reveal the underlying thermal protection mechanism. The Cu thin film helps to dissipate heat along the in-plane direction by reconfiguring the heat flux direction, while excessive heat is assimilated by the paraffin phase change material.

To better understand the thermal behavior of the thermal protection substrate integrated with the wearable electronics, the effect of multiple factors on the maximum temperature is systematically investigated. The results show that the dimensions modeled are the same as those in Fig. 2 except for the thicknesses of the paraffin and thermal protection substrate which are respectively set to 1 mm and 2 mm for better demonstration. Figures 3(a) and 3(b) show the effects of input power and heating duration time on the maximum temperature at the bottom of the PDMS and the thermal protection substrates, respectively. Obviously, the higher the input power is, the higher the maximum temperature is. The maximum temperature can reach 224°C in the PDMS substrate at an input power of 990 mW and a heating duration of 500 s while it reaches only 95°C under the same loading conditions in the thermal protection substrate. This indicates the good temperature reduction efficiency of the thermal protection substrate. The influence of the input power and heating duration time on the percentage of temperature reduction is shown in Fig. 3(c). For all the heating conditions studied, the temperature reduction is above 65%, and the maximum reduction can reach 85%. Moreover, the cooling efficiency is relatively high at the high input powers and short heating durations that exist when short circuits occur. These results show that the thermal protection substrate has excellent temperature management ability for wearable electronics, especially when short circuits occur and a large amount of heat is generated within a short time.

The effects of the radii of the Cu film and paraffin layer on the cooling efficiency of the thermal protection substrate are shown in Fig. 4. This is a more comprehensive geometrical parameter study compared with our previous work^[30]. The input power is set as 660 mW and the heating time is 100 s. As shown in Fig. 4(a), the maximum temperature decreases with the increase in radii of the Cu film and the paraffin layer. Moreover, the radius of the Cu film has a larger effect on the temperature than that of the paraffin layer radius. Figure 4(b) shows the corresponding temperature reduction percentage. It can be observed that the percentage increases with the radii of the Cu film and the paraffin layer. The maximum temperature reduction in the cases studied can reach 88%. Therefore, if space permits, increasing the radius of the metal film can reduce the maximum temperature more effectively than increasing the radius of the paraffin layer.

Fig. 4 (a) The variation of the maximum temperature at the thermal protection substrate bottom surface and (b) the percentage of temperature reduction with the radii of the paraffin layer and the thin Cu film (substrate thickness: 2 mm) (color online)

3 Thermal modeling of wearable electronics device with a thermal protection substrate on skin

An analytical model for the wearable electronics/skin system is established to investigate the thermal management capacity of the thermal protection substrate in practical applications. Figure 5(a) schematically illustrates the axisymmetric modeled system of a wearable electronics device incorporating a thermal protection substrate on a layer of skin. The origin of the cylindrical coordinate system is located at the center of the skin layer bottom. The orientations of the r -axis and z -axis are shown in Fig. 5. The interfaces in the system are located at z_1 , z_2 , z_3 , z_4 , and z_5 . The radii of the circular ultra-soft heater, Cu film layer, paraffin layer, and substrate are still denoted by R_h , R_1 and R_2 , respectively. For simplicity, the skin is assumed to be a uniform, homogenous material with a thickness of 5 mm because the thermal properties of the various layers (i.e., epidermis, dermis, and fat) of skin are similar^[39]. The temperature at the skin bottom is set as 37°C, which is the normal human body temperature. The thermophysical parameters of skin are as follows: $\rho_{\text{skin}} = 1 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$, $c_{\text{skin}} = 2846 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, and $k_{\text{skin}} = 0.37 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ ^[39].

The heater transfer equations in the various regions with different materials can be written as

$$\begin{cases} \rho_{\text{skin}} c_{\text{skin}} \frac{\partial T}{\partial t} = k_{\text{skin}} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right), & r < R_2 \cap 0 < z < z_1, \\ \rho_{\text{PDMS}} c_{\text{PDMS}} \frac{\partial T}{\partial t} = k_{\text{PDMS}} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right), & R_1 < r < R_2 \cap z_2 < z < z_3, \cup z_1 < z < z_2 \cup z_4 < z < z_5, \\ \rho_{\text{paraffin}} \frac{\partial H}{\partial t} = k_{\text{paraffin}} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right), & r < R_1 \cap z_1 < z < z_2, \\ \rho_{\text{Cu}} c_{\text{Cu}} \frac{\partial T}{\partial t} = k_{\text{Cu}} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right), & r < R_1 \cap z_1 < z < z_2. \end{cases} \quad (14)$$

The interfacial conditions at the paraffin/PDMS, paraffin/Cu, and Cu/PDMS interfaces are the same as those in Eqs. (7)–(11) except for the differences in the coordinates of the interfaces. At the PDMS/skin interface, the temperature satisfies

$$T|_{z=z_1^+} = T|_{z=z_1^-}, \quad -k_{\text{PDMS}} \frac{\partial T}{\partial z} \Big|_{z=z_1^+} = -k_{\text{skin}} \frac{\partial T}{\partial z} \Big|_{z=z_1^-}. \quad (15)$$

The boundary conditions give

$$\begin{cases} -k_{\text{skin}} \frac{\partial T}{\partial z} \Big|_{z=0} = T_s, \\ -k_{\text{skin}} \frac{\partial T}{\partial z} \Big|_{r=R_2} = h(T - T_a)|_{r=R_2}, & 0 < z < z_1, \\ -k_{\text{PDMS}} \frac{\partial T}{\partial r} \Big|_{r=R_2} = h(T - T_a)|_{r=R_2}, & z_1 < z < z_5, \\ -k_{\text{PDMS}} \frac{\partial T}{\partial z} \Big|_{z=z_5} = h(T - T_a)|_{z=z_5} - Q \times \text{heaviside}(r(R_h - r)). \end{cases} \quad (16)$$

The axisymmetric boundary gives

$$-k_i \frac{\partial T}{\partial r} \Big|_{r=0} = 0 \quad (17)$$

with i denoting paraffin, Cu, PDMS, or skin.

To ensure close contact with the human skin, the flexible electronics should be thin. The thicknesses of the Cu film, paraffin, and substrate are set as $10\mu\text{m}$, $290\mu\text{m}$, and $600\mu\text{m}$, respectively. The input power is set as 550mW with the heating duration of 54s . Figures 5(b) and 5(c) show the temperature fields at the interface between the substrate and the skin for the PDMS and the thermal protection substrates, respectively. The temperature is maximum at the center of the contact interface, which corresponds to the point P in Fig. 5(a). The thermal protection substrate exhibits an excellent thermal protection effect in which the peak temperature is significantly reduced by 72.9% from 99.3°C to 53.9°C .

Fig. 5 (a) Schematic diagram of axisymmetric model including the skin. The analytically calculated temperature distributions on the interface between skin and (b) PDMS, (c) thermal protection substrates from the analytical results after heating by heaters (heating time: 54s and substrate thickness: 0.6mm). The maximum temperature at the (d) PDMS substrate/skin interface and (e) thermal protection substrate/skin interface with different substrate thickness and heating duration time. (f) The interface temperature reduction at different substrate thickness and heating duration time (color online)

Figures 5(d) and 5(e) show the effects of the substrate thickness and heating duration time on the maximum skin temperature for the PDMS and thermal protection substrates, respectively. Figure 5(f) shows the corresponding percentage of temperature reduction. The maximum skin temperature for the PDMS substrate increases rapidly to over 80°C . In particular, for substrate thicknesses of less than 1mm , which is the typical thickness for wearable electronics, the maximum skin temperature can reach more than 100°C in a few seconds, which is not tolerable for the human body. For the thermal protection substrate, the maximum skin temperature is, in most cases, below 50°C . Even for a small substrate thickness of 0.2mm with a heating time of 400s , the skin temperature reaches only up to 66°C . The effects of the substrate thickness and heating duration time on the temperature reduction are shown in Fig. 5(f). It is observed that the thermal protection substrate can yield a 65% – 85% temperature reduction, which further illustrates the excellent thermal protection effect. Moreover, the percentage of temperature reduction is high for a short heating duration. This indicates that the thermal protection substrate design provides a good avenue to protect skin from adverse thermal effects due to short circuits in the wearable electronics.

4 Conclusions

An analytical transient phase change thermal conduction model accounting for the phase transition process and anisotropic thermal conduction is established to investigate the thermal behavior of wearable electronics integrated with the thermal protection substrate. The validity and accuracy of the analytical method are verified by the good agreement between the analytical results and the experimental and the FEA results. The systematic studies on multiple factors influencing the maximum temperature provide insights into the underlying thermal protection mechanism. The metal thin film helps to dissipate heat along the in-plane direction by reconfiguring the direction of heat flux, while the phase change material assimilates excessive heat. The results show that the thermal protection substrate can substantially reduce the temperature increase when the wearable electronics are in operation or when short circuits and other exothermic faults occur.

These results provide guidance for the optimal design of thermal protection substrates for wearable electronics and shed light on the development of thermal models for thermal management in wearable electronics.

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