Electronic Supplementary Information

A High Heat Dissipation Strategy Based on Multi-Scale Porous Hydrogel and Heat Sink Exhibiting Cooling Capacity Comparable to Forced Air Convection but with Zero Energy Consumption

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Water absorption capacity test of the CHS

The water absorption capacity test was carried out in a room temperature environment. The samples H1, H2, H3 were prepared into slender strips and placed in a suitable glass tube. A big sink at the bottom was used as the water source. The glass tubes were suspended so as not to affect the hydration of the hydrogel. The water absorption height of different samples at different times was recorded in the experiment to characterize the water absorption rate. As shown in Fig. S1, sample H3 with a proper size distribution and larger relative pore throat diameter has much higher capillary force and lower flow resistance, which makes its water absorption performance much better.

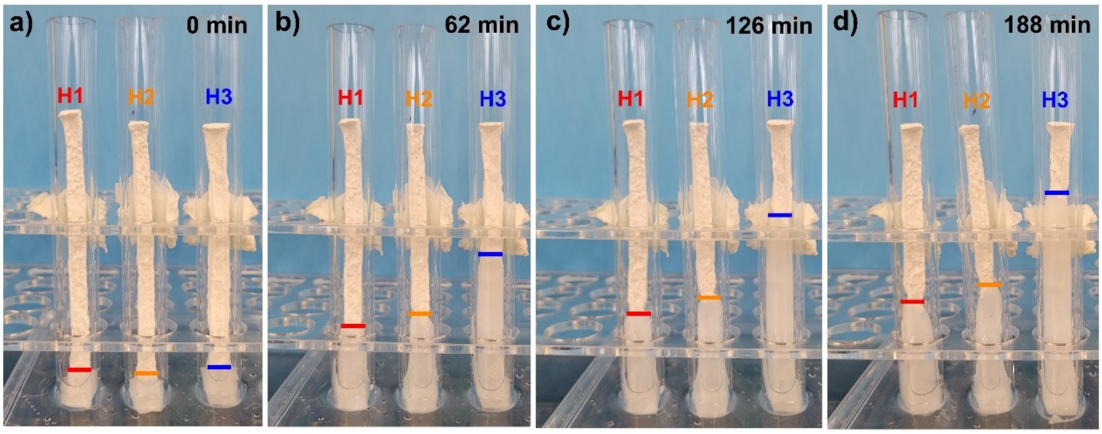

Fig. S1 Water absorption capacity test of the porous hydrogels.

Simulation of the CHS

The schematic illustration of heat dissipation with the CHS and thermal resistance network of the CHS are shown in Fig. 3a and S2, respectively. According to the thermal resistance network model, the theoretical model calculation process of the CHS system is established, as shown in Fig. S3.

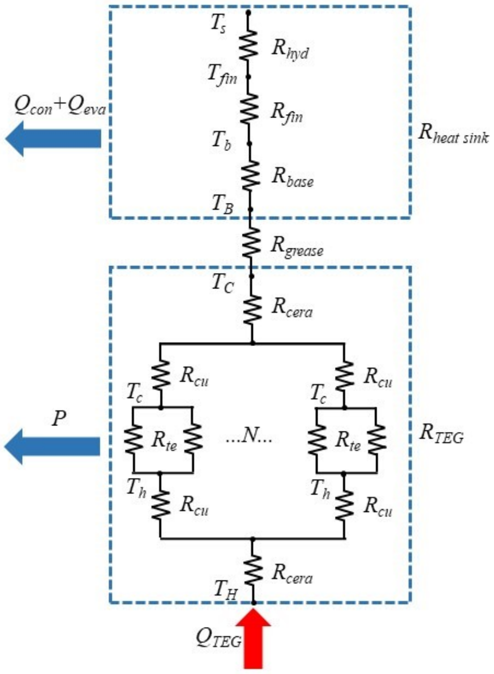

Fig. S2 Schematic of the CHS thermal resistance network.

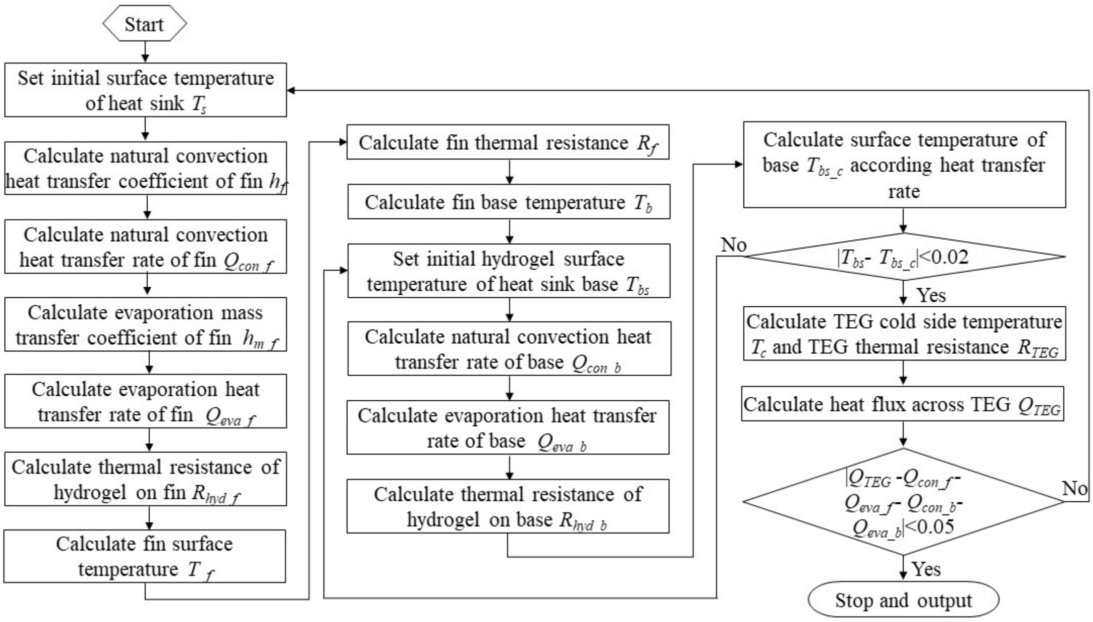

Fig. S3 Schematic of the theoretical model calculation process.

The conduction thermal resistance of each part is as determined follows:

$$R = t/kA \tag{1}$$

where t, k, and A represent the thickness, thermal conductivity, and area of the heat transfer surface, respectively. The thermal resistances of the TEG are given as:

$$R_{TEG} = \frac{2R_{cu} + \frac{1}{1/R_P + 1/R_N}}{n} + 2R_{cera} \tag{2}$$

where R_{cu}, R_{cera}, R_P, and R_N are the thermal resistance of the copper electrode, ceramic substrate, P-leg, and N-leg, respectively. n is the leg pairs of the TEG module.

Both evaporative and convection should be considered when CHS is used for heat dissipation. The convection heat transfer flow of the CHS is expressed as:

$$Q_{con} = hA_{con}(T_s - T_{amb}) \tag{3}$$

$$h = Nu \cdot k_m \cdot s_{fin} \tag{4}$$

where h, A_{con}, T_S, T_{amb}, k_m, and s_{fin} are convective heat transfer coefficient, the area of convective heat transfer, the hydrogel surface temperature, ambient temperature, moist air thermal conductivity, and fin space, respectively. Nu is the Nusselt number, and calculated by the following correlations:[1]

$$Nu = 1/24 \cdot Ra \cdot s_{fin}/L_{fin} \cdot [1 - exp(- 35/(Ra \cdot s_{fin}/L_{fin}))]^{0.75} \tag{5}$$

$$Ra = [g \cdot \beta \cdot (T_s - T_{amb}) \cdot s_{fin}^{3}]/(\alpha \upsilon) \tag{6}$$

$$\beta = 1/T_f \tag{7}$$

$$T_f = (T_s + T_{amb})/2 \tag{8}$$

where Ra, L_{fin}, β, α, and v are the Rayleigh number for heat transfer, fin height, cubic expansion coefficient, thermal diffusivity coefficient of moist air, and kinematic viscosity, respectively.

The evaporation heat transfer flow of the CHS is expressed as:[1]

$$Q_{eva} = q_m \cdot A_{eva} \cdot (\rho_{w\_sat} - \rho_{w\_amb})h_{fg} \tag{9}$$

$$\rho_{w\_amb} = RH \cdot \rho_{w\_amb\_sat} \tag{10}$$

$$q_m = D_{w\_amb} \cdot Sh/L_{fin} \tag{11}$$

$$D_{w\_amb} = 1.877 \times 10^{-10} \times T_f^{2.072} \tag{12}$$

$$Sh = [0.825 + 0.387 \cdot Ra_m^{1/6}/(1 + (0.492/Sc)^{9/16})^{8/27}]^2 \tag{13}$$

$$Ra_m = Gr \cdot Sc \tag{14}$$

$$Sc = v/D_{w\_amb} \tag{15}$$

Where q_m, A_{eva}, ρ_{w_sat}, ρ_{w_amb}, $\rho_{w\_amb\_sat}$, RH, and h_{fg} are the mass transfer coefficient, area of evaporation heat transfer, saturated vapor density, ambient water vapor concentration, water vapor saturation density at ambient temperature, ambient relative humidity, and latent heat for evaporation evaluated at the hydrogel surface temperature, respectively. D_{w_amb} is the diffusion coefficient of water vapor diffusing to the ambient environment, and it can be calculated across correlation 12. Sh, Ra_m, and Sc are the Sherwood number, Rayleigh number and Schmidt number, respectively. Grashof number (Gr) is given by correlations 16-19:[1]

$$Gr = g|\rho_s - \rho_{amb}|L_{fin}^3/(\rho v^2) \tag{16}$$

$$\rho_s = \rho_{w\_sat} + \rho_{air\_s} \tag{17}$$

$$\rho_{amb} = \rho_{w\_amb} + \rho_{air\_amb} \tag{18}$$

$$\rho = (\rho_s + \rho_{amb})/2 \tag{19}$$

where ρ_s and ρ_{amb} are the densities of moist and ambient air, respectively. ρ is the average density, ρ_{air_s} and ρ_{air_amb} are the hydrogel surface and ambient air densities, respectively with respect to T_s and T_{amb}, respectively.

The convection thermal resistance of fins is calculated by correlations 20-23:[1]

$$R_{fin} = 1/(2m \cdot L \cdot L_c \cdot \eta_{fin} \cdot h) \tag{20}$$

$$\eta_{fin} = tanh(c \cdot L_c)/(c \cdot L_c) \tag{21}$$

$$c = \sqrt{2h/(k_{fin} \cdot t_{fin})} \tag{22}$$

$$L_c = L_{fin} + t_{fin}/2 \tag{23}$$

where m, L, η_{fin}, k_{fin}, and t_{fin} are the fins number, fin length, fin efficiency, thermal conductivity, and thickness, respectively. Then, the temperature of upper surface of the substrate can be calculated by the following equations:

$$T_b = Q_{con} \cdot R_{fin} + T_{fin} \tag{24}$$

Similarly, the cold end temperature T_C of the thermoelectric device can be obtained based on the heat flow rate and thermal resistance.

$$T_C = (Q_{con} + Q_{eva}) \cdot (R_{base} + R_{grease}) + T_b \tag{25}$$

Therefore, the heat flow across the TEG is:

$$Q_{TEG} = (T_H - T_C)/R_{TEG} \tag{26}$$

The TEG open-circuit voltage U_{open}, and output power P_{max} are described as follows:

$$U_{open} = n \cdot (S_P + S_N) \cdot (T_h - T_c) \tag{27}$$

$$P_{max} = U_{open}^2/(4n(R^e + 2R_{cu}^e) \tag{28}$$

$$R^e = \rho_P^e t_{leg}/A_{leg} + \rho_N^e t_{leg}/A_{leg} \tag{29}$$

$$R_{cu}^e = \rho_{cu}^e(1 + A_{cera}/2nA_{leg})/ t_{cu} \tag{30}$$

where S_P, S_N, R^e, R_{cu}^e, ρ_P^e, ρ_N^e, ρ_{cu}^e, t_{leg}, A_{leg}, A_{cera}, and t_{cu} are the Seebeck coefficient of P-type leg, Seebeck coefficient of N-type leg, electrical resistance of thermoelectric element, electrical resistance of a copper electrode, electrical resistivity of P-type leg, electrical resistivity of N-type leg, electrical resistivity of copper, thickness of the thermoelectric leg, area of the thermoelectric leg, area of the ceramic substrate, and the thickness of the copper electrode. T_h and T_c are respectively the temperatures of the upper and lower surfaces of thermoelectric leg, which can be calculated by correlations 31-32:

$$T_h = T_H - Q_{TEG}R_{cera} - Q_{TEG}R_{cu}/n \tag{31}$$

$$T_c = T_C + Q_{TEG}R_{cera} + Q_{TEG}R_{cu}/n \tag{32}$$

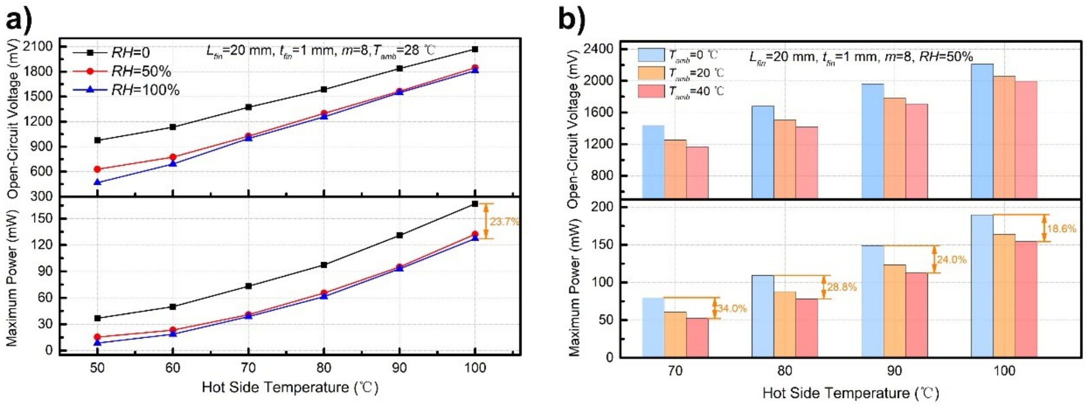

Fig. S4 a) Influence of ambient temperature on the electricity generation performance of a TEG with CHS. b) Influence of ambient humidity on the electricity generation performance of a TEG with CHS.

References

[1] T. L. Bergman, A. S. Lavine, F. P. Incropera, D. P. DeWitt, *Fundamentals of Heat and Mass Transfer*, Wiley, 2018.