Mushroom-like rGO/PAM Hybrid Cryogels with Efficient Solar-heating Water Evaporation

*Chuan-Shan Hu[1], Hui-Juan Li[1], Jia-Yun Wang[1], Abdul Haleem[1], Xi-Chuan Li[1], Muhammad Siddiq[2], Wei-Dong He[1,] *(email: wdhe@ustc.edu.cn)*

1: CAS Key Laboratory of Soft Matter Chemistry, Department of Polymer Science and Engineering, University of Science and Technology of China, Hefei, Anhui 230026, China

2: Department of Chemistry, Quaid-i-Azam University, Islamabad, 45320, Pakistan

Supporting Information

Monomer conversion and gel fraction of (cryo-)polymerizations

After the (cryo-)polymerization, the obtained cryogel/hydrogel was kept in distilled water for 6 h. Then, the swollen cryogel/hydrogel was taken out and the absorbed water was squeezed out into the previous beaker. Bromide aqueous solution (2 wt%) was dropped into the collected water to check the presence of un-polymerization monomer. Brown color hardly faded for the reported (cryo-)polymerizations, indicating that almost all the monomers did polymerize.

To check the gel fraction of cryogel/hydrogel, dried and weighted cryogel/hydrogel was swollen in distilled water for at least 48 h. Every 6 h, the water was placed with fresh distilled water. Then, the swollen cryogel/hydrogel was lyophilized to constant weight. Based on the ratio of weights before and after this swelling, gel fraction of cryogel/hydrogel was determined to be more than 95 % for all the reported gels.

N_2 adsorption-desorption isotherms of different cryogels

Nitrogen adsorption-desorption technique is widely adopted to determine the porosity and total surface area of micro/meso-porous materials (Anovitz, L.M. D.R. Cole, D.R., Characterization and Analysis of Porosity and Pore Structures, *Pore-Scale Geochemical Processes* 2015, **80**, 61-164.), but it is in reservation for its practice in macro-porous polymeric materials. However, the hysteresis loops of all PAM, GO/PAM and rGO/PAM cryogels are Type Ⅳ isotherm, characteristic of macro-porous feature.

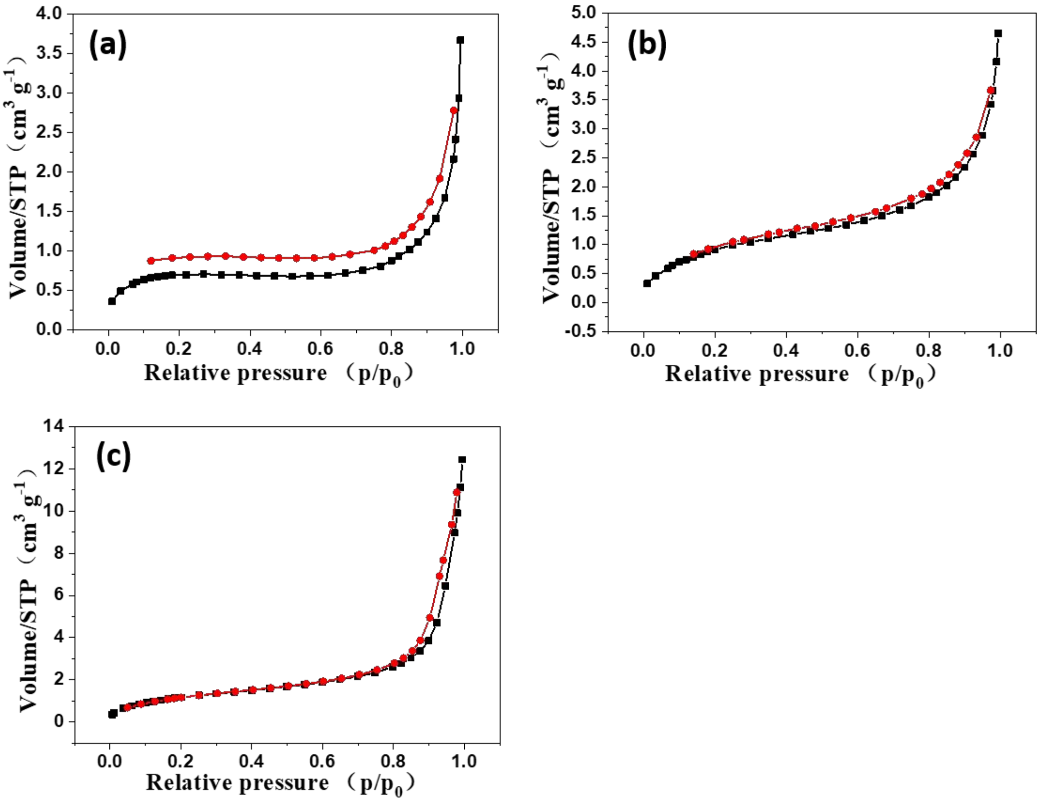

Figure S1 N_2 adsorption-desorption isotherm of PAM cryogel (a), GO/PAM cryogel (a) and rGO/PAM cryogel (C)

One-sun illumination of rGO/PAM hydrogel mushroom during solar-heating evaporation

As shown in Figure S2A, rGO/PAM hydrogel mushroom has flat surface of mushroom pileus. After one-sun illumination for 0.5 h, the rGO/PAM hydrogel layer became dehydrated and the mushroom pileus turn curled upwards Figure S2B.

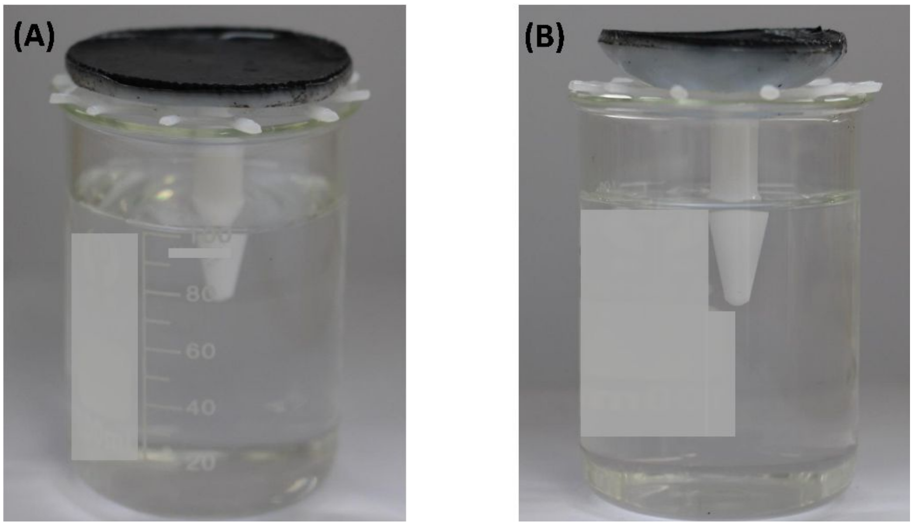

Figure S2 Photos of rGO/PAM cryogel mushroom (A) and rGO/PAM mushroom hydrogel (B) after one-sun illumination for 0.5 h.

UV-vis-NIR reflectance and transmittance of rGO/PAM hydrogel

UV-vis-NIR reflectance and transmittance spectrum of rGO/PAM hydrogel are shown in Figure S3. From those, UV-vis-NIR absorbance spectrum of rGO/PAM hydrogel can be obtained, as shown in Figure 2D.

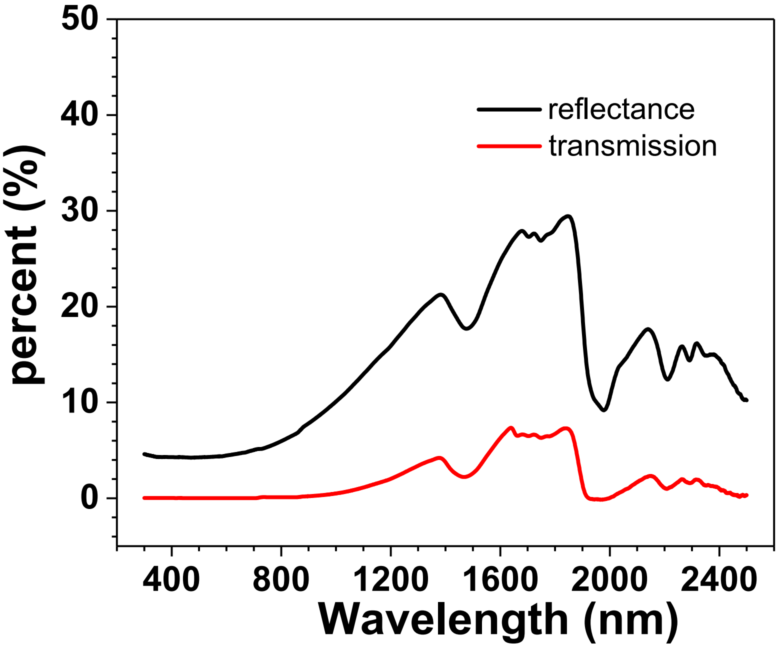

Figure S3 UV-vis-NIR reflectance and transmittance spectra of rGO/PAM hydrogel.

Thermal conductivity of different cryogels

The density (ρ) of cryogel was determined based on the mass and volume of cryogel. In this work, 0.16 g/cm^3 was regarded as the density of three cryogels. Thermal diffusivity (α) of cryogel was measured by Laser thermal conductivity meter (LFA-467) and the specific heat capacity (C) of cryogel was was characterized through differential scanning calorimetry (DSC, Q2000). Thus, thermal conductivity (λ) of cryogel was obtained as $\lambda = \rho \times \alpha \times C$.

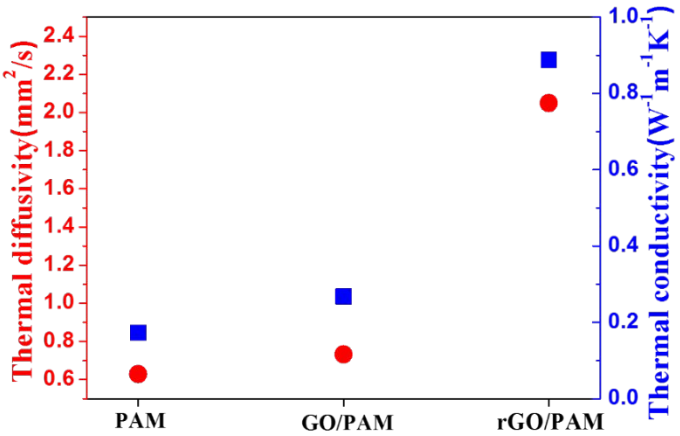

Figure S4 Thermal diffusivity and thermal conductivity of PAM cryogel, GO/PAM cryogel and rGO/PAM cryogel

Temperature record of dry rGO/PAM cryogel pileus

Dry rGO/PAM cryogel mushroom without water reservoir was illuminated under one-sun incident light for half an hour, the temperature of pileus could reach 84 ºC (Figure S4).

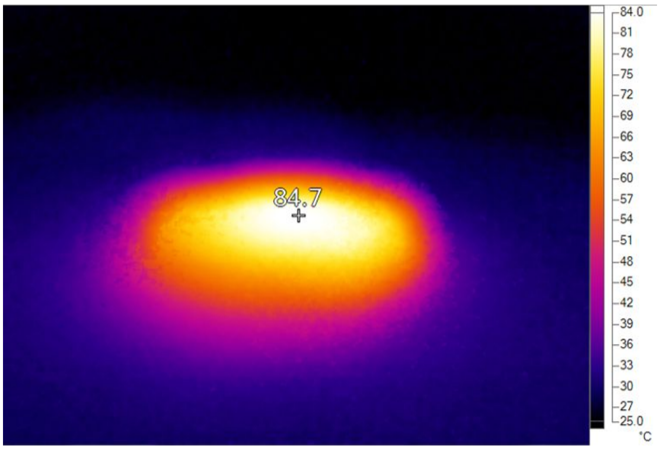

Figure S5 IR images of dry rGO/PAM cryogel after being irradiated under one sun for half an hour.

Solar-heating evaporation for PAM cryogel mushroom

Mushroom device composed of only PAM cryogel has solar-heating evaporation rate of 0.45 $kg \cdot m^{-2} \cdot h^{-1}$ under one-sun illumination (Figure S5).

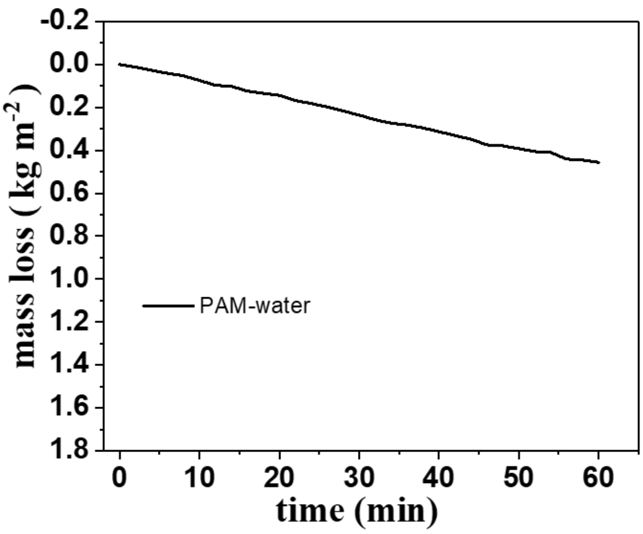

Figure S6 Time-dependent mass loss of water for PAM cryogel mushroom under one-sun illumination.

Comparison of solar-heating evaporation for hydrogel and cryogel mushroom

Comparison between the solar-heating evaporation of rGO/PAM cryogel mushroom and rGO/PAM hydrogel mushroom with the same shape and size was performed at one-sun illumination (Figure S6). Mass loss for hydrogel is lower than that of cryogel at each interval, and decreased obviously with interval increase.

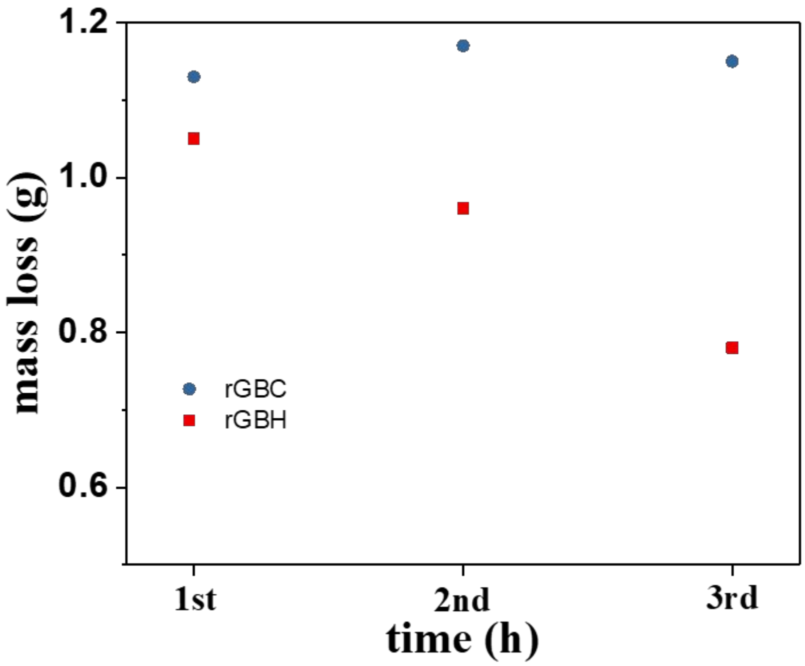

Figure S7 Mass loss of water for rGO/PAM hydrogel (rGBH) and rGO/PAM cryogel (rGBC) under one-sun illumination within different intervals of our hour

Solar-heating evaporation cycle of salty water with rGO/PAM cryogel mushroom

Solar-heating evaporation cycle of salty water with rGO/PAM cryogel mushroom was performed under one-sun illumination for ten times. The repetition is pretty well with evaporation rate of 1.34~1.54 $kg \cdot m^{-2} \cdot h^{-1}$.

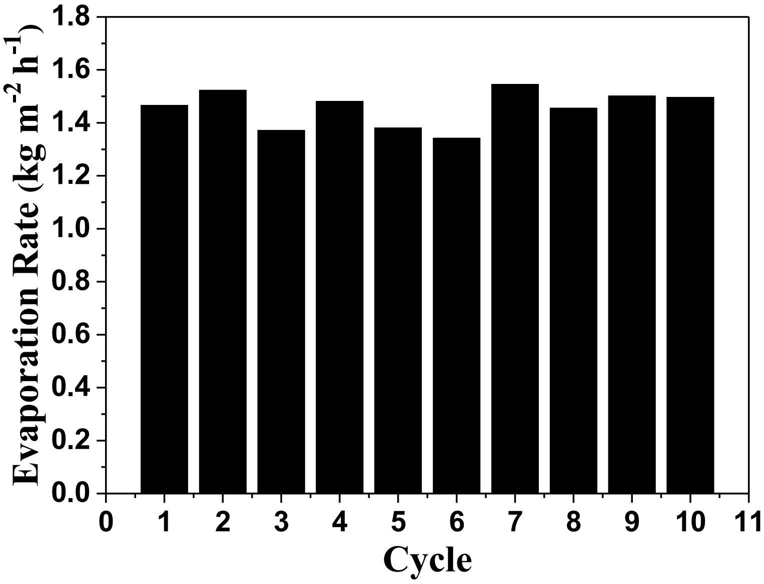

Figure S8 Solar-heating evaporation cycle of salty water with rGO/PAM cryogel mushroom under one-sun illumination

Collection of condensed water and its potassium content

The condensed water from solar-heating evaporation was collect with the apparatus as shown in Figure S8A. The content of potassium ion was determined to be 0.822 mg/L (Figure S8B) through ICP-MS analysis. Figure S8B also exhibit the criteria of World Health Organization (WHO) and the US Environmental Protection Agency (US-EPA) for drinking water

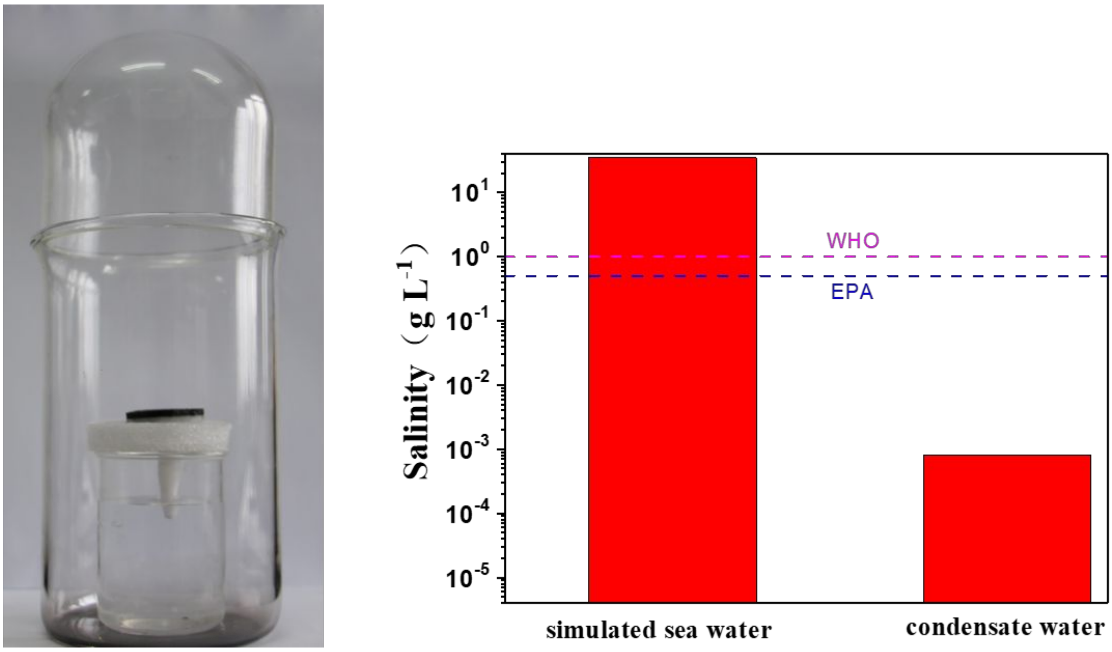

Figure S9 Photo of apparatus for collecting condensate water (A) and the contents of potassium ion in simulated seawater and condensed water (B)

Thermal analysis calculation of evaporation process

The total energy reached the surface of mushroom-like rGO/PAM hybrid cryogel is kept at 1 kW/m^2 and it was consumed through five main routes: (1) water evaporation, (2) reflection, (3) conductive heat loss from the top layer to the bulk water, (4) convection heat transfer from the top layer to environment, (5) radiation heat transfer from the top layer to the environment. The energy transfer process is shown in the following equation:

$$P_{in} = Q_{cond} + Q_{conv} + Q_{rad} + Q_{ref} + Q_{eva}$$

Where P_{in} is the total energy incident onto the surface of evaporation device, in this work, the power density is 1000 W/m^2.Q_{cond} is the conductive heat loss from the top layer to bulk water. Q_{conv} is the convection heat loss from the top layer to the environment. Q_{rad} is the radiation heat loss from the top layer to the environment. Q_{ref} is the light power reflected by the surface of the evaporation device. Q_{eva} is the energy consumed for steam generation.

(1) Water evaporation

As has calculated in the main text, the average evaporation efficiency is 86.8%. So energy consumed for evaporation is about 868W/m^2.

(2) Reflection

According to the UV-Vis spectra, the reflectance of rGO/PAM cryogel is about 5.4%. So reflection loss is 54 W/m^2.

(3) Conduction heat loss

The conduction heat loss could be calculated by the following equation:

$$Q_{conv} = -kA_s\frac{d_T}{d_X}$$

where k is the thermal conductivity of the stipe swollen with water, which is about 0.522Wm-^{1}K^{-1}.A_s is is the surface area of the stipe. $\frac{d_T}{d_X}$ is the gradient of temperature of the stipe. As a result, conduction heat loss is about 21.3W/ m^2.

(4) Convection heat loss

The convection heat loss could be calculated by the following equation:

$$Q_{cond} = A_t h_t(T_t - T_e)$$

where A_t is the surface area of top layer, h_t is the convection heat transfer coefficient, which is about 5 W/m^2/K. T_t is the average temperature of the surface of top layer, which is about 36℃. T_e is the temperature of the environment, which is about 25℃. As a result, convection heat loss is about 55 W/m^2.

(5) Radiation heat loss

The radiation heat loss could be calculated by the following equation:

$$Q_{rad} = \varepsilon\sigma A_t(T_t^4 - T_e^4)$$

where ε is the emissive rate, which is about 0.95. σ is the Stefan-Boltzmann constant, T_t, T_e and A_t are the same as described above. As a result, radiation heat loss is about 0.07W/ m^2.

The total energy consumed through the five strategies is 998.37 W/m^2, which is near to the power of incident light. The deviation is within the acceptable range.