An Interfacial Solar-Driven Atmospheric Water Generator Based on a Liquid Sorbent with Simultaneous Adsorption–Desorption

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Water scarcity is one of the greatest challenges facing human society. Because of the abundant amount of water present in the atmosphere, there are significant efforts to harvest water from air. Particularly, solar-driven atmospheric water generators based on sequential adsorption–desorption processes are attracting much attention. However, incomplete daytime desorption is the limiting factor for final water production, as the rate of water desorption typically decreases very quickly with decreased water content in the sorbents. Hereby combining tailored interfacial solar absorbers with an ionic-liquid-based sorbent, an atmospheric water generator with a simultaneous adsorption–desorption process is generated. With enhanced desorption capability and stabilized water content in the sorbent, this interfacial solar-driven atmospheric water generator enables a high rate of water production (≈0.5 L m⁻² h⁻¹) and 2.8 L m⁻² d⁻¹ for the outdoor environment. It is expected that this interfacial solar-driven atmospheric water generator, based on the liquid sorbent with a simultaneous adsorption–desorption process opens up a promising pathway to effectively harvest water from air.

With increasing population and degrading environment, freshwater scarcity is becoming a major global challenge. As atmospheric water is estimated to be ≈10% of all fresh water on earth, water harvesting from air is attracting significant attention with several strategies such as fog water capture and dewing collection. Recently, solar-driven atmospheric water generator based on sequential adsorption–desorption processes are attracting much attention. However, incomplete daytime desorption is the limiting factor for final water production, as the rate of water desorption typically decreases very quickly with decreased water content in the sorbents. Hereby combining tailored interfacial solar absorbers with an ionic-liquid-based sorbent, an atmospheric water generator with a simultaneous adsorption–desorption process is generated. With enhanced desorption capability and stabilized water content in the sorbent, this interfacial solar-driven atmospheric water generator enables a high rate of water production (≈0.5 L m⁻² h⁻¹) and 2.8 L m⁻² d⁻¹ for the outdoor environment. It is expected that this interfacial solar-driven atmospheric water generator, based on the liquid sorbent with a simultaneous adsorption–desorption process opens up a promising pathway to effectively harvest water from air.

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As shown in Figure 1c, the setup is composed of two interconnected containers filled with liquid sorbent for adsorption and desorption. In the adsorption area, liquid sorbent adsorbs water vapor from the atmosphere. In the desorption area, water in liquid sorbent is desorbed continuously by interfacial solar heating to generate vapor, which condenses to liquid water flowing into the collection grooves. In the adsorption area, liquid sorbent keeps harvesting atmospheric water, which transfers to the desorption area. Therefore, steady state can be reached, in which the water content of desorption area is maintained. It is confirmed by COMSOL Multiphysics simulation, as shown in Figure 1d. The outer part (dark blue) is the absorption area, the inner part (light blue) is the desorption area. Water in the adsorption area can transport to the desorption area continuously and rapidly. When reaching the steady state, the water content of desorption area \( (0.94 C_0) \) maintains close to that of adsorption area \( (C_0) \) (Figure 1d) (more details in Section SA, Supporting Information). Hence, it confirms that this AWG design with simultaneous adsorption–desorption can maintain high water content in the sorbent and therefore enable effective desorption over long time. Our design possesses several unique advantages. First, the introduction of interfacial solar heating realizes heat localization, which increases the surface temperature of sorbent in the desorption area, and enable effective desorption of water out of the liquid sorbent. Second, because of the simultaneous adsorption–desorption process, which keeps water content in the sorbent sufficient, high water production rate can be achieved and maintained. Therefore, it is expected that ISAWG can enable effective desorption and high rate of water production.

In order to realize this design, there are a few requirements for both interfacial solar absorbers and liquid sorbents. For interfacial solar absorbers, it is important that the absorbers have broadband and efficient light absorption. For sufficient water transport to absorbers, it is ideal that the surface is hydrophilic. In addition, the absorber should have good mechanical and chemical stability for long-term recycling. For liquid sorbent, it is critical to have high hygroscopicity to enable large amount of water adsorption at a wide range of relative humidity (RH). Besides, liquid sorbent should have excellent physical, chemical stability, and compatibility with the interfacial solar absorbers to ensure stable performances over long term. To satisfy these requirements, we choose a hydrophilic carbon fiber membrane (CFM) as the interfacial solar absorber and a highly hygroscopic ionic liquid ([EMIM][Ac]) as liquid sorbent, as explained in more details next.

The choice of sorbents is critical for the overall performance. Ionic liquid is a stable organic solvent consisting of cations
and anions. Due to the strong polarity of characteristic groups contained such as acetate anion, this kind of ionic liquid molecule usually interacts with water molecule by hydrogen bond, representing ionic liquid consisting of 1-ethyl-3-methyl-imidazolium cation ([EMIM]+) and an acetate anion ([Ac−]) (Figure 2a), is chosen as it is an excellent sorbent working at a wide range of RH (20–80%), commonly used for gas-capturing and converting solvents.[42,43] In addition, Troshenkova et al. reported the hygroscopicity of [EMIM][Ac] solution and found this type of ionic liquid can absorb up to 27% of water from air at room temperature.¹⁴ Fourier-transform infrared spectroscopy (FTIR, Figure 2b) result of [EMIM][Ac] shows different vibrations of chemical bond. The peaks located at 1402 and 1569 cm⁻¹ correspond to the C=O symmetrical stretching vibration and the C=O asymmetrical stretching vibration of acetate anion, which indicates the [EMIM][Ac] molecule will be hygroscopic because of interaction of hydrogen bond.

The adsorption process of [EMIM][Ac] is illustrated in Figure 2c. Water molecules in the air are captured by [EMIM][Ac] molecules on the surface through hydrogen bond, and then diffuse toward the internal solution because of concentration gradient. At surface, first neighbor water molecules are bonded by a [EMIM][Ac] molecule (≈93.64 kJ mol⁻¹), then the polarity of these water molecules changes, resulting in that the second neighbor water molecules are bonded by first neighbor ones. Hence, water molecules can be bonded by [EMIM][Ac] molecule layer by layer (Figure 2d). However, the bond energy will decrease with number of water molecules adsorbed and then stabilize at ≈53.99 kJ mol⁻¹ due to the weaker hydrogen bond interactions between water molecules (Figure 2e).

To examine the water adsorption performance of [EMIM][Ac] quantitatively, we measured water uptake of [EMIM][Ac] under different RHs, as shown in Figure 2f. At 10, 20, 40, and 60% RH, [EMIM][Ac] exhibits water adsorption capacity of 10, 18, 27, and 63% of weight after 16 h, respectively. It is noteworthy when the RH reaches 80%, that the water uptake increases to ≈118%, corresponding to 1.18 g g⁻¹ (gram of water per gram of [EMIM][Ac]). The water adsorption isotherms of [EMIM][Ac] are also shown in Figure S9 (Supporting Information).

For comparison, we also measured the water adsorption capacity of other two common liquid sorbents (LiCl saturated solution (40 wt%) and CaCl₂ saturated solution (50 wt%)) under two different RHs (80 and 20%). It is noteworthy that here we chose the liquid state of LiCl and CaCl₂ sorbents to compare on the same level with ionic liquid. At 80% RH, water uptake of [EMIM][Ac] is 10 and 30% higher than that of LiCl solution and CaCl₂ solution, respectively (Figure 2g). At 20% RH, CaCl₂ solution is even gradually dehydrated and [EMIM][Ac] still presents a significantly better water adsorption capacity (Figure 2h). All the performances suggest that [EMIM][Ac] is an excellent sorbent for a wide range of RHs.

Paradoxically, the high binding energy of [EMIM][Ac] with water molecule not only makes it an excellent sorbent but also makes it challenging for water desorption. Conventional solar heating method heats up water volumetrically, leading to low temperature at the surface of desorption, hardly providing sufficient energy to break the strong bond between [EMIM][Ac] and water molecule. Conversely, by localizing absorbed solar energy on the surface of water, interfacial solar heating can enable effective desorption from [EMIM][Ac] with significantly higher temperature. Here, we choose a hydrophilic carbon fiber membrane (CFM) as an absorber for interfacial solar heating because of its high absorptivity of sunlight and excellent chemical stability (Figure 3a). The absorption spectrum in Figure 3b shows that the CFM has ≈95% absorption of solar energy. Meanwhile, the characteristics of scanning electron microscopy (SEM) and Raman spectra of CFM before and after atmospheric water harvesting confirm its significant mechanical and chemical stability (Figure S3, Supporting Information).

The CFM absorber was floated on the [EMIM][Ac] solution containing 120% water to examine the desorption performance under the solar simulator (1 kW m⁻²) (Figure S4, Supporting Information). We used an infrared camera to clearly record the temperature change of CFM during the desorption process under 1 sun intensity (Figure 3c). It is clear that there are two different stages. In the first stage, the temperature of the absorber increases from the initial state of 24.5 to 75.6 °C in first 6 h, indicating a rapid temperature increase (8.5 °C h⁻¹, state 1, Figure 3d). At this stage, the water content decreases from 120 to 111%, presenting a significantly high desorption rate, the maximum rate reaching 0.808 L m⁻² h⁻¹ (Figure 3e), and the average rate of ≈0.33 L m⁻² h⁻¹ by utilizing interfacial solar heating at this stage. During the second stage, which is the last 6 h, the temperature of the absorber increases slowly at an average rate of 1.85 °C h⁻¹ and the desorption rate decreases because of the low water content (<25%) in the [EMIM][Ac] (Figure 3d). For comparison, conventional solar-driven heating is typically volumetric without heat localization on the surface (Figure S5, Supporting Information). Water content of this desorption process only decreases a little (<9%) after 12 h illumination and even maintains still high about 111% (Figure 3d). Therefore, the desorption rate (averaged) of whole process is only ≈0.017 L m⁻² h⁻¹ (Figure 3e). It is clear that as the interaction force of hydrogen bond between water and [EMIM][Ac] is stronger than that among water molecules (Figure 2e), interfacial solar heating can enable higher desorption rate and more effective desorption out of [EMIM][Ac], compared to conventional solar-driven approach.

To demonstrate the concept of ISAWG with simultaneous adsorption and desorption, we designed a device with two parts for adsorption and desorption (Figure 4a). The sorbent [EMIM][Ac] is put in the glass container of adsorption part for harvesting water from air. The desorption part is composed of a transparent case with grooves connected for collecting water. The CFM as an absorber is floating on the surface of liquid within the desorption part. Figure 4b shows a photo of the actual device, which is put within a big transparent box for stable temperature and RH (The specific parameters of this device are shown in Figure S6a,c, Supporting Information). Initially, we used 200 g [EMIM][Ac] solution with initial 100% water content in the glass container. As shown in Figure 4c, the amount of adsorbed water and collected water both increases over time, proving that our designed device can adsorb and desorb water simultaneously. The adsorbed water refers to water adsorbed during the whole process, which can be tracked by the balance. The collected water refers to water collected out of grooves containing the condensed water (Experimental Section).
In order to exhibit the best performance of our device, we chose the high RH (80%) to operate. At lower RH, it also works (seen in Section SH, Figure S8, Supporting Information). As a result, the water production rate maintained stable around 0.5 L m\(^{-2}\) h\(^{-1}\) all the time (Figure 4c) and a total of 30.32 g water was produced in 12 h, because of sufficient water content in the sorbent. For comparison, we measured the water production rate using the adsorption–desorption
separated device (specific parameter of this device is shown in Figure S6b, Supporting Information) with the same [EMIM][Ac] as sorbent and CFM as solar absorber under 1 sun intensity. It is shown in Figure 4d that in total 26.54 g water was obtained in 12 h and the water production rate fell from ≈0.58 to ≈0.24 L m⁻² h⁻¹ within 6 h limited by low water content in the adsorption–desorption separated device. It is noteworthy that although the desorption area of our designed ISAWG is smaller than that of conventional AWG device, which suggests the lower solar energy input (Figures S6a and S4b, Supporting Information), the total water production of our design is still higher. The results above clearly illustrate that ISAWG with simultaneous adsorption–desorption realizes not only more stable water production rate but also higher water production.

To evaluate the stability of this device for water harvesting under different solar intensities, we conducted a long-term cycling experiment (Figure 4e). During the entire process, the water mass continues to increase, illustrating that water adsorption proceeds all the time under both light-on and light-off condition. When light is switched on and water is desorbed from [EMIM][Ac] solution, the averaged water production rate reached ≈0.7 L m⁻² h⁻¹ under 1.6 sun, which is higher than that under 1 sun (≈0.5 L m⁻² h⁻¹). We also performed FTIR on the [EMIM][Ac] before and after the test (Figure S7, Supporting Information). No peaks variation suggests that [EMIM][Ac] is very stable throughout the test. Moreover, the ion concentration in the collected water totally satisfies the WHO/EPA standard (Figure S10, Supporting Information).

Figure 3. Desorption test results of [EMIM][Ac]. a) SEM of the CFM absorber for interfacial solar heating. The inset is the optical photo of absorber. b) Absorption spectrum of the absorber used in the interfacial solar desorption. The red line is the absorption rate and the brown line is the spectrum of solar radiation. c) Infrared photos of the absorber under 1 sun illumination over time. d) The temperature of absorber surface over time and comparison of desorption performance between interfacial solar heating and conventional solar bulk heating; water content change over time during the desorption process. e) Desorption rates over time for interfacial solar heating and conventional solar bulk heating.
Figure 4. Indoor performance. 

a) Schematic and b) optical photo of newly designed ISAWG. 

c) Collected, adsorbed water mass change and water production rate of ISAWG over time. 

d) Water mass change and water production rate of the adsorption–desorption separated device using interfacial solar heating over time. The inset shows the optical photo of the device. 

e) Water mass change and production rate of ISAWG over long time with multiple cycles of on-off light sources.
The device based on simultaneous adsorption/desorption also realized a good water harvesting performance outdoor at different RH (Figure 5a–c). Under a summer day (Nanjing, China) with ~70% RH beside a lake, we achieved 17.96 g water in total in 7 h (Figure 5d inset), equivalently producing 2.8 L m$^{-2}$ water d$^{-1}$, which to our knowledge is among the highest water production compared with previous works (Figure 5e). It is noteworthy that the temperature of [EMIM][Ac] in the adsorption area maintained near room temperature, despite the high temperature in the desorption area, which is the signature of interfacial solar heating (Figure 5d). When placing the device on the lawn with ~50% RH (Figure 5c), we still achieved the water production of ~1.7 L m$^{-2}$ water d$^{-1}$ (more details shown in Figure S11, Supporting Information). It further manifests that our designed ISAWG can be operated under different RH and is promising in the practical application.

In summary, we have proposed and demonstrated the concept of ISAWG to enhance the desorption process and to improve the atmospheric water production. As an example, by utilizing [EMIM][Ac] as a liquid sorbent and a carbon fiber membrane as an interfacial solar absorber, we achieved a significantly stable water production rate of ~0.5 L m$^{-2}$ h$^{-1}$ under 1 sun and 80% RH indoors, and produce over 2.8 L m$^{-2}$ water d$^{-1}$ outdoors, among the highest reported. As this approach can be generalized for various liquid sorbent and corresponding interfacial solar absorbers, it is expected that this
Experimental Section

Materials Characterization: The morphology and microstructure of the carbon fiber membrane were characterized by scanning electron microscopy (TESCAN MIRA3 SEM) operating at 5 kV. The FTIR spectrum of the [EMIM][Ac] solution was obtained by a Nexus 870 spectrometer. The optical transmittance and reflectance spectra of the carbon fiber membrane were measured in the range of 200–2500 nm with a Shimadzu UV3600 spectrophotometer attached to an integrating sphere (ISR-3100). FLUKE Ti 100 infrared camera was used to take infrared photographs.

Device Fabrication: Simultaneous adsorption and desorption device consists of two parts: a glass container (20 × 20 × 3 cm) and a transparent case with four brackets (Figure S6a, Supporting Information). The side walls of case as the condenser are the low thermal conductivity materials (poly(methyl methacrylate) (PMMA)) and the top surface is the transparent material (poly(ethylene terephthalate) (PET)) with 93% light transmittance. The adsorption–desorption separated device is similar to the transparent case only with a sealed bottom (Figure S6b, Supporting Information). In addition, the specific parameters of the transparent box for temperature and RHs control are shown in Figure S6c (Supporting Information).

Experimental Procedure: For the adsorption experiment (Figure 2), 6 g of [EMIM][Ac] solution (6 g) to stay at the state of high water content (120%). Then it was spread over a 6.5 cm diameter petri dish. A hydrophilic carbon fiber membrane (6.5 cm diameter) as absorber was put on the top of foam floating on the surface of the liquid. The foam (4.5 cm diameter) was used to ensure the membrane floating on the liquid level to realize interfacial heating. The whole experiment was carried in a constant temperature and humidity chamber to control the temperature (25 °C) and different RHs. The mass change was recorded by the computer over time. –6 g of different kinds of common sorbents (50% wt CaCl2 and 40% wt LiCl) was used to carry out a comparative experiment in the same method and conditions.

In the desorption experiment (Figure 3), deionized water (12 g) was mixed into [EMIM][Ac] solution (6 g) to stay at the state of high water content (120%). Then it was spread over a 6.5 cm diameter petri dish. A hydrophilic carbon fiber membrane (6.5 cm diameter) as absorber was put on the top of foam floating on the surface of the liquid. The foam (4.5 cm diameter) was used to ensure the membrane floating on the liquid level to realize interfacial heating. The whole experiment was carried under the solar simulator (1 kW m−2) with a Shimadzu UV3600 spectrophotometer attached to an integrating sphere (ISR-3100). FLUKE Ti 100 infrared camera was used to take infrared photographs. Similarly, the bulk heating experiment was on the same condition only without the absorber. Two desorption curves are shown in Figure 3d.

For the adsorbing and desorbing water simultaneously experiment (Figure 4c), the whole container was filled with 200 g [EMIM][Ac] solution with initial 100% water content. The desorption area was covered by a hydrophilic carbon fiber membrane (8 × 8 cm) on foam to float on the surface of liquid. A xenon lamp (1 kW m−2) with 8 cm diameter light spot was used to simulate illumination. Environmental conditions were stabilized at 25 °C and 80% RH throughout the experiment by a closed cabinet. Similarly, adsorption–desorption separated device with the same water content of [EMIM][Ac] solution was carried out in the same experimental conditions as comparative experiment. In the light switching on-off cycle experiment (Figure 4e), xenon lamp was on for 2 h and then off for 2 h as a cycle. At the first 2 cycles, it was under sun intensity, and then it was increased to 1.6 sun at the next two cycles, was back to 1 sun at last cycle. Adsorption water mass was recorded by the balance directly and the production water was taken out to weigh the mass every hour in both experiments. All the light intensity was calibrated by solar power meter. In addition, this section we added a semiconductor chilling plate (3 W; 12 VDC) on the back wall of the device to enhance the condensation process.

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.

Keywords

adsorption, interfacial solar heating, ionic liquid, water harvesting

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