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Preview

Moisture Farming with Metal-Organic Frameworks

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In a recent issue of *Science*, Kim et al. describe a device that captures water vapor from the atmosphere at low relative humidity by using a metal-organic framework as the active sorbent. This first-of-its-kind water harvester can be powered by only solar thermal energy.

Water and energy are increasingly interlinked. More and more of our water comes from energy-intensive sources such as desalination, pumped ground water, or massively diverted rivers; all of our energy production requires water, from hydroelectric dams to the water turned to steam in coal-fired or nuclear power plants. The growing global demand for water is projected to create a nearly two-billion-megaliter shortage by 2030, approximately one-quarter of the total current freshwater usage.[1] Supply problems resulting from climate change, desertification, and aquifer depletion are only exacerbating the demand growth brought on by population and agriculture expansion. Water shortfalls are particularly severe in regions with an annual average relative humidity (RH) around or below 30% and with limited water infrastructure (e.g., North Africa and Northern China).[2] Additionally, many of these dry geographical areas are landlocked and isolated, leading to a very limited scope for mature and large-scale water-purification technologies, i.e., reverse osmosis (RO) and multi-stage flash. As a consequence, atmospheric humidity, which makes up 0.4% of global liquid fresh water, can constitute the most abundant water source in such areas with limited precipitation and ground water. In their recent publication in *Science*,[3] Kim et al. describe a device that can capture water from the atmosphere in environments with a RH as low as 20% and that can be powered by only solar thermal heating. This novel device utilizes a metal-organic framework (MOF) as the active water sorbent, which, because of its superb water-uptake profile, enables water harvesting in dry climates with a relatively low energy requirement.

Harvesting fresh water from the atmosphere in a locally distributed manner where it is most needed could eliminate the large-scale distribution network and upfront capital required for incumbent technologies such as RO desalination. However, existing atmospheric water generators (AWGs) employ technology that mandates high humidity levels. At 100% RH, capturing water from the air is as simple as hanging up a high-surface-area fabric and watching the water drip into a vessel.[4] With slightly lower humidity levels, down to approximately 60% RH, dewing can be used: a method that essentially refrigerates large volumes of air down to the dew point.[5] Developing a technology for producing water from air in an energy-efficient manner in areas with an average RH lower than 60%, where it is often most needed, remains an important challenge.

An alternative to dewing at low RH is to use a sorbent material with a high affinity for water vapor to capture ambient humidity. After the adsorption process, the sorbent is then heated to release the concentrated water vapor, which can then be condensed at ambient temperature. Previous AWG devices or concepts have employed sorbents such as concentrated brine[6] or zeolites.[7] These sorbents are competent for water capture below 5% RH; however, their strong affinity for water necessitates high regeneration temperatures, an important drawback from an energy-efficiency standpoint.

In choosing a sorbent, a balance must be struck between a high affinity for water vapor and the energy required for desorption. A material that binds water more strongly will function at lower RH, but more energy will be required to release and then collect the water. Additionally, a stepwise adsorption of water vapor is desirable. Because the transition between the full and the empty states can be achieved with a minimal temperature swing, a sorbent with a steep water uptake in a narrow RH range will be more efficient than a sorbent with a gradual adsorption over a range of humidity. Commonly employed solid sorbents either bind water too strongly, showing significant water uptake even at 0% RH (e.g., zeolites), or have low, broad uptakes (e.g., silica gel), making them unsuitable for an efficient AWG.

MOFs are designer sorbents by virtue of their modular composition, allowing for tuning of the water uptake step by varying factors such as pore size and hydrophilicity. Additionally, their large and uniform internal voids allow for record capacity and stepwise uptake of water vapor. In their demonstration

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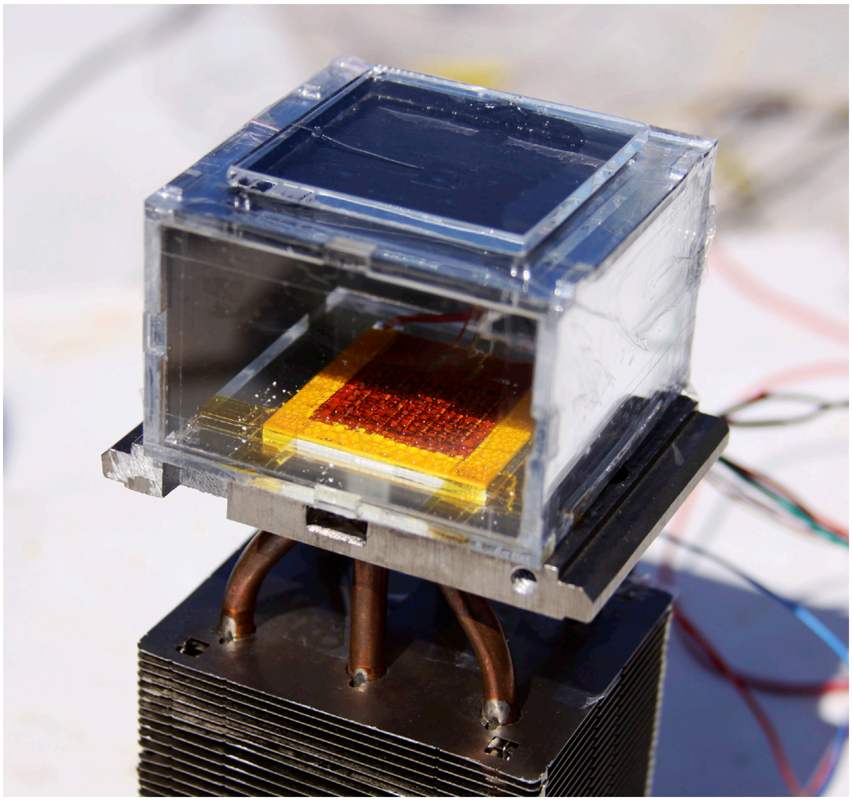

Figure 1. The Prototype Water-Harvesting Device during the Process of Harvesting Water Powered by Natural Sunlight

Water droplets can be seen forming on the condenser layer, the orange and yellow film. The MOF layer is above the condenser hanging from the top of the enclosure and is placed directly below the glass window in order to receive incident radiation. Image used with permission from Kim et al.

device, Kim et al. employed the well-studied MOF-801, a porous material consisting of Zr_6 oxo nodes and fumarate linkers, as the active sorbent.[8,9] This MOF has a water-vapor uptake step at approximately 20% RH, as well as regeneration at temperatures as low as 65°C. For demonstration purposes, Kim et al. tested MOF-801, packed into a porous copper foam to enhance thermal conductivity, in an environmental chamber paired with a solar simulator. After one cycle of adsorption at 20% RH and 35°C, followed by desorption by heating under a 1 kW m^{-2} solar flux to 80°C, 0.24 L water per kg MOF was harvested in the actively cooled condenser.

In order to test the water-harvesting cycle under environmental conditions, the authors designed and constructed a prototype water-harvesting device. The prototype consists of a MOF-801 layer inside an enclosure coupled to a condenser (Figure 1). The device, placed outside on a roof, adsorbed vapor overnight. The following day, as the sun rose, incident radiation heated the MOF layer and desorbed the water vapor, which was then collected by the condenser. In this way, the device can utilize the natural variation in temperature and RH between day and night to drive the water-harvesting cycle. The authors estimate that $\sim$0.3 L kg^{-1} can be harvested in this manner under ambient conditions of 65% RH and 25°C. This passive cycle using an adsorbent at low RH is analogous to dew forming on grass overnight at 100% RH and then evaporating the following morning under the heat of the sun.

Passive solar thermal water harvesting could be especially advantageous in desert regions, where there is commonly a large difference between daytime and nighttime temperatures and RHs. Even in the driest deserts on Earth, such as the Sahara and the Atacama, the RH rises above 30% during nighttime. A passive AWG inside every home in the desert could provide plentiful drinking water while eliminating the infrastructure and distribution network required for conventional centralized water-purification technologies.

The work of Kim et al. represents an important proof-of-concept device that can harvest water by using only passive solar thermal energy. It should thus serve as a beacon for other researchers looking to explore water-harvesting methods. Further innovative solutions such as this one will be necessary for addressing the challenges of water production, purification, and distribution as demand grows and as supply is locally constrained. Further improvements in AWG technology can be expected both from a device-engineering perspective and from designing new water sorbents with larger uptakes and tailored water affinities for adsorption at specific RHs that also minimize the energy required for desorption.[10] The atmospheric water-harvesting field is well positioned to greatly expand in the wake of this groundbreaking paper.

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