Insights of moisture capture from air for heating and cooling

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Received: March 3, 2024; Accepted: April 11, 2024; Published Online: April 25, 2024; https://doi.org/10.59717/j.xinn-energy.2024.100022

Citation: Chen Z., Yang X., and Wang R. (2024). Insights of moisture capture from air for heating and cooling. The Innovation Energy 1(2): 100022.

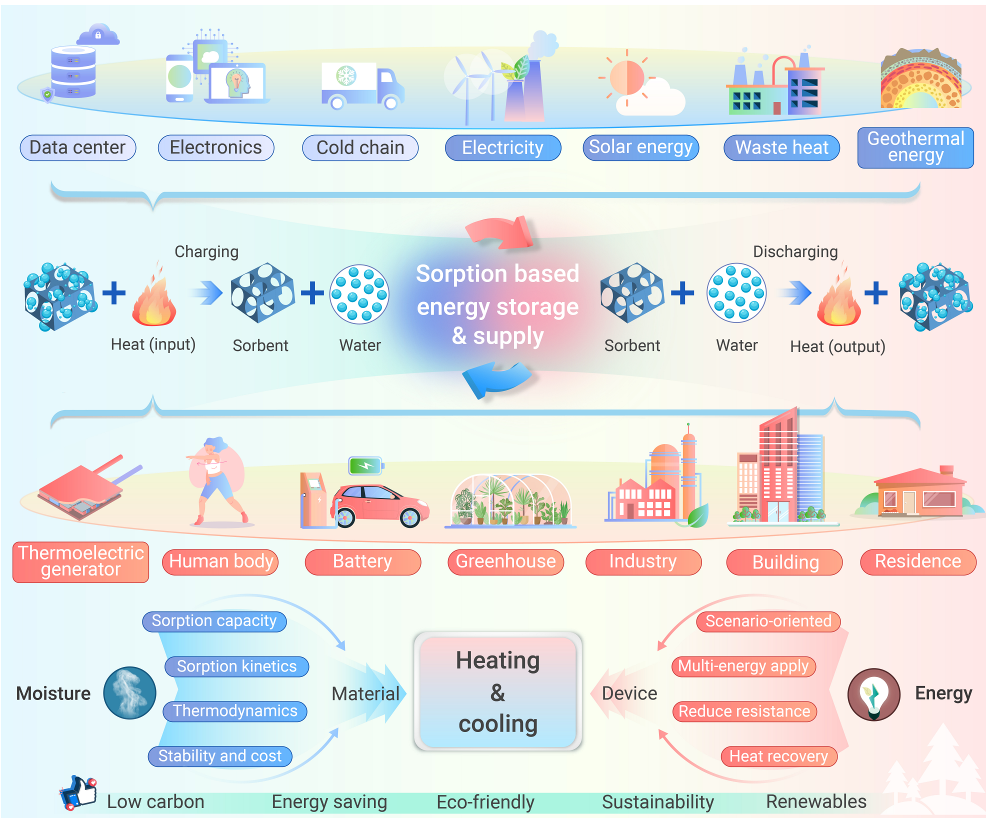

Figure 1. Concept, methods, and applications of STSS by capturing moisture from air.

Energy plays a vital role in the human life. Population growth and social progress urge the excessive demand for natural resources, resulting in severe climate change and imminent energy crisis.[1] Among the terminal energy utilization for residential, industrial and commercial purposes, heating and cooling account for a large share. The imbalance between energy production and demand leads to a shortage risk. To address this issue, policies calling for low carbon, energy saving and storage have been implemented in recent years.

Sorption-based thermal energy storage and supply (STSS), as an emerging thermochemical storage method, can realize sustainable heat and cold storage and supply based on the reversible reaction between moisture and sorbents without temporal and geographic restrictions (Figure 1). Separate moisture sorption and desorption processes help to decouple heating and cooling demand flexibly. Diverse heat sources like solar energy, industrial waste heat, or heat generated by electronics can be adopted for water desorption. Adoption of cost-effective renewables and green operation process also provide a viable option to decarbonize heating and cooling. However, the sorbent selection and system design to meet specific application demands is still a challenge. In the era of global energy innovation, increasing attention is driving STSS forward.

STATE OF THE ART OF STSS

For the moisture sorption process, heat is released due to the physical or chemical interaction between water molecules and sorbents, such as van der Waals forces, hydrogen bonds, electrostatic forces, or chemical bonds. The captured water molecules are stored as liquid water inside the sorbent. This exothermic effect exhibits promising potential for heating and the output power is governed by the properties of sorbents such as sorption enthalpy and water sorption capacity. For the water desorption process, heat is needed to overcome the interaction between water molecules and sorbents. The stored liquid water evaporates into water vapor and escapes from the sorbent. This endothermic effect shows considerable prospect for passive cooling through consuming the unwanted thermal energy. However, account for the strong water affinity of traditional sorbents like silica gel, molecular sieve or hygroscopic salts, more sorption heating researches were conducted before instead of desorption cooling researches. By now, diverse sorbents with mild water affinity could be heated by moderate regeneration temperature. Metal-organic framework coating and hydrogel demonstrated notable cooling performance on the operating electronic devices[2] and photovoltaic plates.[3] Salt-based composite sorbents were preferably used in both sorption heating and desorption cooling studies due to their relatively high water sorption capacity and sorption enthalpy.

Along with promoting sorbent properties, system design also gets more attention in recent years. The system of STSS can be divided into closed and open systems depending on whether the sorbate comes from the evaporator or the atmosphere. For the closed system, external heat source could be cooled by providing thermal energy to desorb sorbent in the charging process and evaporate sorbate in the discharging process. While the heat released by both sorbent sorption of discharging and sorbate condensation of charging can be utilized for space heating. For the open system, it is directly connected with the atmosphere for heat and mass exchange. Thus, adjustable strategies like internal and external loops, active and passive desorption, could be adopted to achieve both seasonal heating and cooling targets. No matter for sorption heating or desorption cooling, the requirements for sorbents is similar, namely high water sorption capacity, rapid sorption-desorption kinetics, efficient heat and mass transfer, and long-term stability. While for the sorbent bed, from packed bed to coating-based heat exchanger or self-assembled porous bed, diverse modes are conducted for better overall performance.

CHALLENGES AND OPPORTUNITIES FOR STSS

Although the feasibility of STSS has been verified by plenty of sorbents and devices, the reported heat/cold energy storage density (ESD) and discharging power density (DPD) still have a gap with actual demand. ESD depends on three factors of the sorbent, namely the sorption enthalpy ΔH (kJ/kg), water sorption capacity w (g/g), and the mass density ρ (kg/m^3). While DPD is mainly affected by ΔH, ρ, and water sorption rate v (g/(g·h)). Under the premise of a certain sorbent bed size, to obtain a high ESD, it is inevitable to use large amounts of sorbents. However, the accumulation between sorbents hinders the mass transfer rate, resulting in a low DPD. This trade-off between energy density and power density partly limits the development of STSS. Moreover, due to the limited water sorption capacity of the sorbent, the sorption-heating and desorption-cooling processes usually last for a certain time, unable to satisfy the demand for long-term thermal management. More realistically, the adoption of salt-based sorbents exists a risk of solution leakage and corrosion, which needs periodic check to ensure its normal operation. Compared with other thermal energy storage methods, the initial investment cost for STSS is high. Although solar energy or waste heat could be induced into the system as the heat source, its instability and uncontrollability will affect the output performance.

To address the above issues, series of fundamental researches and pilot projects were conducted.[4] The enhancement for STSS is mainly from two aspects. One is sorbent optimization. High water sorption capacity and rapid sorption kinetics benefit high thermal energy and power densities. The next-generation sorbent design should focus on creating abundant hygroscopic factors/sorption sites, high porosity with large specific surface area, and directional pore channel to reduce mass transfer resistance. Meanwhile, both high thermal conductivity and latent heat of vaporization for sorbent help to build ideal thermodynamic properties. The other aspect for STSS enhancement is system innovation. All considerations should be made from the viewpoint of application scenario-oriented research. It's commonly noticed that there is a mismatch between the performance at device and material level. Rational arrangement of the flow channel inside sorbent bed enables sufficient mass transfer between moisture and the sorbents. Simulations adopting models including sorption isotherm, kinetics, and thermodynamics to predict the heat and mass transfer process within the sorbent bed are also beneficial to system design especially for large-scale STSS. To address short-term and discontinuous operation issue, innovative strategies such as partition operation of a single sorbent bed like rotary wheel, alternate operation of multiple sorbent beds, solar energy-waste heat-electricity synergistic utilization, and heat pump assistance are attemptable.[5] This kind of multi-energy complementarity can also promote the stability of heating/cooling output for user side. Besides, enhanced insulation, multistage heat recovery and precise control of the energy consumption with intelligent thermostats are vital for device to realize high energy efficiency.

The transition to sustainable STSS system brings a combination of challenges and opportunities. Currently, demand for cooling in buildings and industries is comparable to the demand for heating due to the increasing demand for air conditioning, preservation of food and medicine, and cooling of machine, etc. Therefore, highly efficient sorbent desorption to meet cooling capacity demand is getting more focus. From heat dissipation of human body and electronic devices such as laptops and cellphones to the cooling of data centers, sorption-based cooling can be applied to almost any scenario due to a variety of sorbents available with moderate regeneration temperatures. Especially for data center that is in operation all year round, the surplus heat generated by power consumption is large and stable, but the temperature is not high, making the recovery and utilization of data center waste heat a challenging problem worth exploring. STSS can adopt low-grade heat for desorption making the sorbent regeneration more energy-efficient and low-carbon emissions. The heat released by the subsequent sorption process can be used to meet the heating and hot water needs of surrounding buildings, thus achieving efficient utilization of energy and improving thermal economy.

SUMMARY AND PROSPECTS

In conclusion, STSS, as a promising energy storage and utilization technology, demonstrates unlimited potential to relieve the mismatched energy supply and demand for heating and cooling. Despite current low power density, short lifetime, long cycle and high cost, the prominent advantages of high energy density, multi-energy drive, good flexibility, no pollution and reliable safety push STSS towards broader prospect satisfying both heating and cooling demands in diverse scenarios. To overcome the drawbacks for strong market competitiveness, the development of new sorbents with low synthesis cost and better performance in water sorption capacity, sorption kinetics and thermodynamics is imperative. The innovation of system should focus on the proper coupling between components for high efficiency and try to explore more energy-efficiency measures further reducing the energy consumption and total cost.

STSS helps to integrate high share of renewable energy and support the transition to a predominantly renewable-based energy system thus reducing the need for costly grid and the dependence on fossil fuels. Its contribution to energy saving and emission reduction, and inherent superiority in capturing moisture from air for distributed energy supply lay the foundation for its application potential in energy-efficient building and low-carbon life. Investments to drive technological innovation combined with holistic energy policy to scale up renewables adoption, can unlock the rapid growth in STSS deployment. By further adding a condenser to collect the water from sorbent desorption for utilization, a more complete system could be integrated demonstrating serviceability in industry and agriculture. In the near future, it's believed that a closer nexus between energy, water, air, and food will be established along with the booming development of STSS for a better earth.

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FUNDING AND ACKNOWLEDGMENTS

This work was supported by the Grand Research Project of National Natural Science Foundation of China [No. 52293411] and the Fundamental Research Funds for the Central Universities (Shanghai Jiao Tong University) [No. 23X010201008]. The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript.

DECLARATION OF INTERESTS

Ruzhu Wang is an Editorial Board member of The Innovation Energy and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group. The other authors declare no conflicts of interest.