

Retraction: A Solar Collector-Based Atmospheric Water Harvesting Device Integrated with Silica Gel Adsorbents

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Abstract

In this study, an integrated solar collector – silica gel air-water harvesting device was designed and constructed. The system operates on the adsorption – desorption cycle driven by a solar vacuum tube collector, enabling continuous water extraction from ambient air through alternating adsorption bed operation. The device consists of an adsorption bed unit, a solar thermal unit, and a condensation unit, featuring a compact structure and high energy utilization efficiency. Experiments were conducted using color-indicating silica gel particles (3 – 5 mm) as the adsorbent, and a prototype device was tested for adsorption – desorption – condensation performance. Results show that under ambient relative humidity conditions of 25% – 85%, the silica gel adsorption bed, after 22 h of adsorption, initiated desorption at 90 °C and sustained stable operation at 110 °C for 2 h, yielding 51 g of fresh water. These findings confirm the effective coupling between the silica gel adsorbent and the solar-driven desorption strategy, providing an experimental basis and technical support for subsequent modular expansion, integrated operation, and engineering applications.

Keywords

Atmospheric water harvesting; Solar energy; Adsorption; Water yield

1. Introduction

Freshwater scarcity has become one of the most pressing global issues in the 21st century. According to the World Bank's assessment, approximately two-thirds of the world's population faces varying degrees of water stress for part of the year, among whom around 500 million people suffer from severe water shortage on a long-term basis.[1].Although traditional large-scale water conservancy projects (such as seawater desalination) can alleviate local freshwater scarcity to a certain extent, they

generally face problems including high investment costs, long construction cycles and complex operation and maintenance. In addition, such projects are difficult to deploy efficiently and achieve rapid water extraction in remote areas like offshore islands and desert interiors—where power grids are weak, populations are sparse and the environment is arid[2].

The water vapor storage capacity in Earth's atmosphere is approximately $1.29 \times 10^4 \text{ km}^3$, equivalent to about 10.3% of the total capacity of global freshwater lakes ($1.25 \times 10^5 \text{ km}^3$). It is worth emphasizing that even in extremely arid regions with annual precipitation of less than 100 mm—such as the Sahara Desert—the absolute humidity of the near-surface air remains within the range of $4 \sim 8 \text{ g} \cdot \text{m}^{-3}$ [3-4]. This indicates that through material science innovation and process design optimization, it is feasible to achieve efficient water vapor capture and condensation in low-humidity environments[5]. The technological development based on this idea is promoting the application of distributed water purification systems in a wider range of arid and semi-arid regions.

Currently, atmospheric water harvesting technologies are mainly classified into three categories: refrigeration-based condensation, fog collection, and adsorption-based water harvesting. The refrigeration-based condensation method reduces the air temperature below the dew point through compression refrigeration, thereby promoting the supersaturation and condensation of water vapor into liquid water. However, this technology has limitations such as high energy consumption, large volume, and strong dependence on the power grid, which restrict its applicability in areas with insufficient electricity supply[6]. The fog collection method relies on large-scale wire meshes to capture fog droplets in the air, featuring advantages such as simple structure and low energy consumption. However, it is significantly affected by geographical and climatic conditions, making it difficult to increase water production[7]. In contrast, adsorption-based water harvesting technology exhibits its unique advantages due to its excellent environmental adaptability. With the development of materials science, especially the application of metal-organic frameworks (MOFs), effective water harvesting has been achieved even under conditions of only 10% relative humidity[8]. More importantly, this technology can be coupled with solar thermal energy systems, thereby promoting the realization and popularization of off-grid distributed water supply devices.

The core principle of adsorption-based water harvesting technology lies in the adsorption-desorption cycle mechanism, and its operation process can be divided into two key stages[9]. In the first stage, water vapor in the air is efficiently captured by porous adsorbent materials through physical interactions. This process relies on the material's specific surface area, pore structure, and surface hydrophilic functional groups, among other characteristics. In the second stage, thermodynamically driven controlled heating of the water-laden adsorbent is achieved, allowing the adsorbed water molecules to desorb, condense, and be collected as liquid water. The main

scientific challenge of this technical system lies in the development of high-performance adsorbent materials. Existing studies have shown that silica gel exhibits excellent performance in water vapor adsorption. Essa et al. [10] found through experiments based on solar stills that the daily water yield of silica gel particles can reach 400 mL/m². Sleiti et al. [11] used silica gel as an adsorbent in a 12-hour cycle experiment in the designed water collection system, and the results showed that 1 kg of silica gel can produce 159 g of water. In addition to single adsorbent materials, composite solid adsorbents have attracted widespread attention due to their advantages of controllable cost, stable performance, and high cycle efficiency [12]. Common composite adsorbent matrices include silica gel [13], ordered mesoporous silica materials [14], and activated carbon [15], etc. Among them, composite salt adsorbents have become a research hotspot due to their higher cyclic adsorption capacity, with lithium chloride [16 – 17] and calcium chloride [18 – 19] being the most representative. Aristov et al. further proposed impregnating hygroscopic salts (such as CaCl₂ [18 – 19] and LiBr [20]) into porous matrices (such as SWS-1L [21] and MCM-41 [22]) to prepare composite adsorbents with better performance. However, most current composite materials still struggle to achieve high adsorption capacity while maintaining efficient desorption performance at low temperatures. Adsorbent bed structure design is another key link in adsorption-based water harvesting technology, with its optimization goal of improving heat transfer performance and desorption rate to shorten the adsorption-desorption cycle [9]. Gordeeva et al. used 250 – 350 g of adsorbent and achieved a desorption temperature of 80 – 90 °C under natural light conditions; the water adsorption capacity of 100 g of composite adsorbent reached 50 g, but the adsorption equilibrium required about 50 – 60 h, and the desorption process also took 30 h [23]. Ji et al. developed a small-scale solar-driven freshwater production system, adopting MCM-41/CaCl₂ composite adsorbent and a direct stacking structure to increase adsorption area and adsorption mass [24]. However, this system has problems such as high adsorbent cost, simple device structure, and limited filling capacity, which restrict its large-scale application. AM Hamed et al. pointed out that atmospheric water harvesting efficiency is closely related to adsorption area and mass transfer coefficient, and proposed the use of a corrugated adsorbent bed structure to increase the effective area [25]. Nevertheless, the use of flexible fabrics to support salt solutions results in low packing density and insufficient model accuracy, with the device's daily water yield per unit area only reaching 1.5 kg. Recently, the team led by Wang Ruzhu from Shanghai Jiao Tong University has constructed a coupled system, adopting electric heaters to provide desorption heat for the adsorbent bed, forming a typical "indirect heating" desorption structure. Its operating principle is as follows: air is heated by electric heaters and then flows through the adsorbent bed to achieve desorption of the adsorbent [9]. Although this scheme can meet the requirements of thermal desorption, its utilization rate of re-

newable energy is relatively low. To improve this deficiency, the team further proposed replacing the electric heating device with solar vacuum tube collectors—heating air through the vacuum tubes, and then introducing the hot air into the adsorbent bed via an air circulation pump to realize the desorption process [26]. This design fully reflects the renewable and modular characteristics of solar energy, but its split structure (i.e., the vacuum tube collectors and the adsorbent bed are arranged separately) still has problems of insufficient system compactness and large energy loss due to relying on the air circulation pump for heat transfer.

In view of the current research status, this paper proposes a more compact and efficient design concept: eliminating the intermediate air transportation link and directly integrating the solar vacuum tube collector with the adsorbent bed. Specifically, by directly filling the adsorbent bed inside the solar vacuum tube collector, solar radiation not only heats the air inside the vacuum tube but also acts directly on the adsorbent, thereby achieving a rapid and efficient thermal desorption process. In this study, COMSOL simulation software is used for numerical analysis of the internal water vapor mass fraction distribution and air velocity field of the adsorbent bed structure. The integrated structure design significantly improves system energy efficiency and operational stability, providing a new design path and theoretical basis for solar-driven adsorption-based water harvesting technology.

2. Design of the Experimental Setup

2.1. System Structure and Component Layout

To verify the proposed solar collector-based atmospheric water harvesting device integrated with silica gel adsorbent, this study first carried out the design and construction of the experimental setup. The overall structure of the device is shown in Figure 1, mainly consisting of condensers, solar vacuum tube collectors, adsorbent materials, condensation units, valves, and air pumps, among other components.

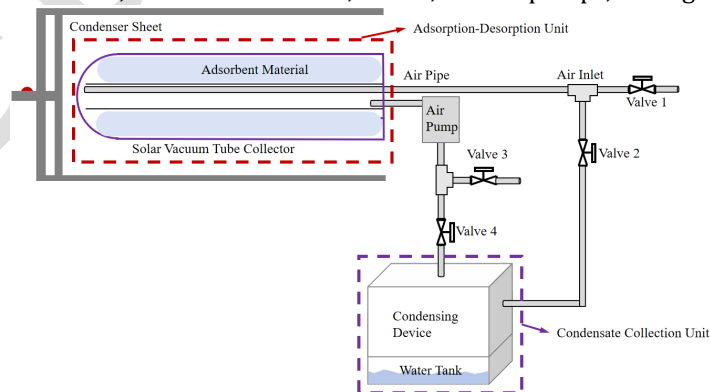


Figure 1. Overall schematic diagram of the device

2.2. Design of the Adsorption-Desorption Unit

The adsorption-desorption unit is mainly composed of condenser lenses, solar vac-

uum tube collectors, and adsorbent materials. Color-changing silica gel particles are selected as the adsorbent, with a particle size of 3 – 5 mm. This material is blue before adsorbing moisture and turns pink after adsorption, and the color change can intuitively reflect its water-containing state (as shown in Figure 2). In the experiment, the color-changing silica gel particles were uniformly filled inside the solar vacuum tube collector to form a compact adsorbent bed, whose structure is shown in Figure 3. The adsorbent bed design includes an air inlet and an air outlet: the inlet is connected to an air pipe, and the end of the pipe extends to the bottom of the vacuum tube to ensure that external air fully flows through the adsorbent layer; the air pipe at the outlet is located at the opening of the vacuum tube for guiding air out.

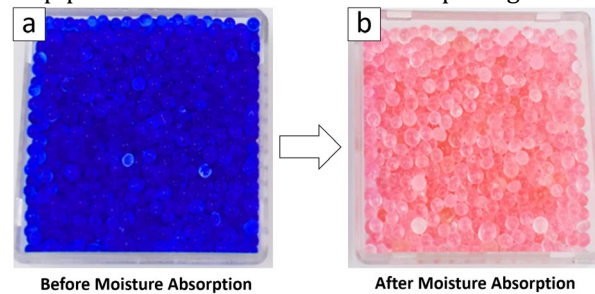


Figure 2. Color change diagram of color-changing silica gel particles before and after moisture absorption

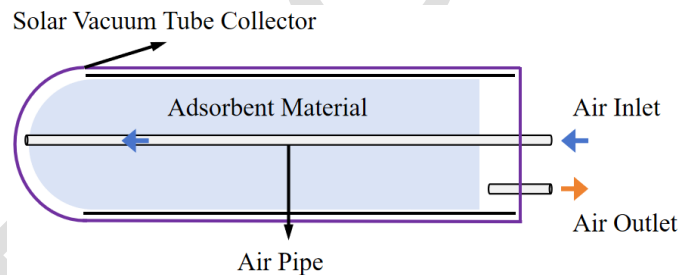


Figure 3. Structural diagram of the adsorption bed

2.3. Design of the Condensation and Collection Unit

The condensation and collection unit is designed to receive the high-temperature and high-humidity gas from the adsorption-desorption unit, enabling condensation phase change on the surface of the condensation fins. For heat dissipation of the condensation device, a 12V DC fan with a current of 0.4A is adopted. It removes the heat from the condensation fins through aluminum heat dissipation fins, ensuring that the temperature of the condensation fins remains consistently below the dew point temperature of the high-humidity steam. As shown in Figure 4 (Structure Diagram of the Condensation Device), the condensation device integrates condensation fins, heat dissipation fins, and a forced convection fan.

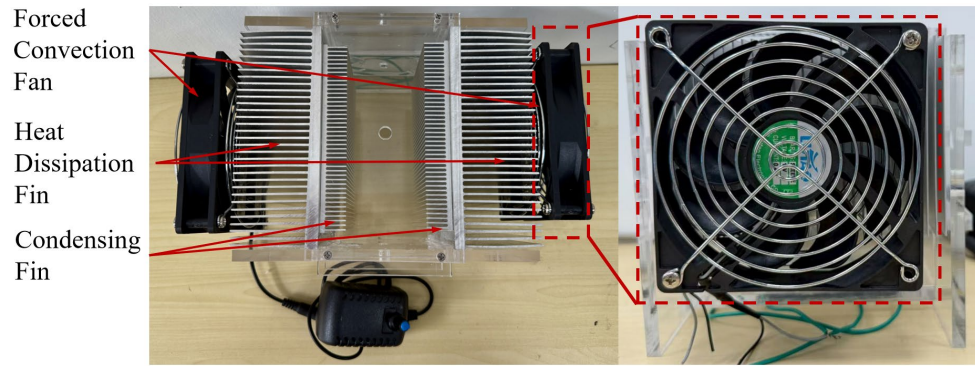


Figure 4. Condensation Device Structure Diagram

2.4. Experimental Procedure and Data Measurement Methods

The adsorption experiment was conducted on the roof of a building at the Institute of Mechanics, Chinese Academy of Sciences, Haidian District, Beijing, with the adsorption phase lasting 22 hours. The mass of the device was recorded before and after the adsorption experiment to calculate the total adsorption capacity Q . The adsorption capacity per unit mass q of the adsorbent material can be calculated using Formula (2-1):

$$q = \frac{Q}{m} \quad (2-1)$$

Wherein

Q : Total adsorption mass(g),

M : Adsorbent mass(g),

Q : Adsorption capacity per unit adsorbent(g/g).

After the completion of adsorption, switch to the desorption-condensation mode. The adsorbent material is heated by the solar vacuum tube collector under natural light conditions. When the temperature of the adsorbent material reaches 90°C , desorption is initiated to release water vapor, which enters the condensation device through a conduit. The condensation device is weighed separately before and after the adsorption experiment, and the mass of condensed water is obtained using the mass difference. This further enables the evaluation of the system's water production capacity and condensation collection efficiency.

3. Experimental Results

The designed atmospheric water harvesting device is shown in Figure 5 (Experimental Device). It is mainly composed of two parts: the adsorption-desorption unit and the condensation-collection unit. The adsorption-desorption unit, air pump, and condensation-collection unit are connected together via silicone hoses in accordance with the overall schematic diagram of the device shown in Figure 1.

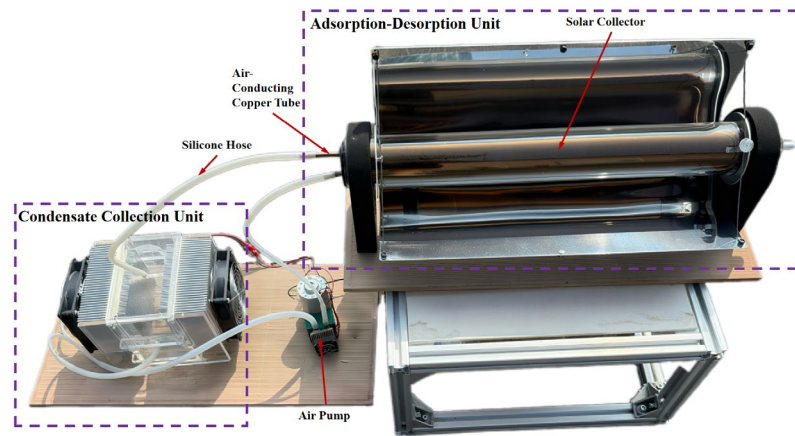


Figure 5. experimental apparatus

The experiment was conducted to evaluate the performance of the designed atmospheric water harvesting device on the roof of a building at the Institute of Mechanics, Chinese Academy of Sciences, located at No. 15 West North Fourth Ring Road, Haidian District, Beijing, from 14:00 on June 23 to 12:00 on June 24, 2025. The on-site ambient temperature and relative humidity are shown in Figure 7 (Temperature and Relative Humidity Data).

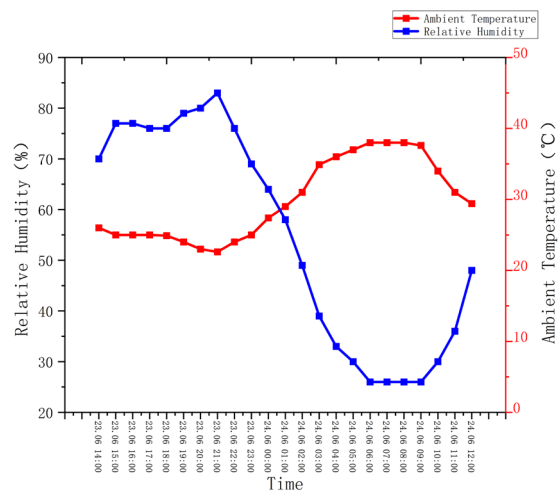


Figure 7. Temperature and Relative Humidity Data

3.1. Adsorption Performance

922.4 g of adsorbent was filled in the adsorbent bed. During the adsorption phase, the system operated continuously for 22 hours, and the adsorbent bed was placed under natural environmental conditions for water vapor collection. The total mass of the device was weighed before and after adsorption—Figure 9 shows the weighing process: (a) before the start of the adsorption experiment, (b) after the end of the adsorption experiment. The total mass of the system before adsorption was 2689.7 g, and after adsorption, it was 2756.0 g.

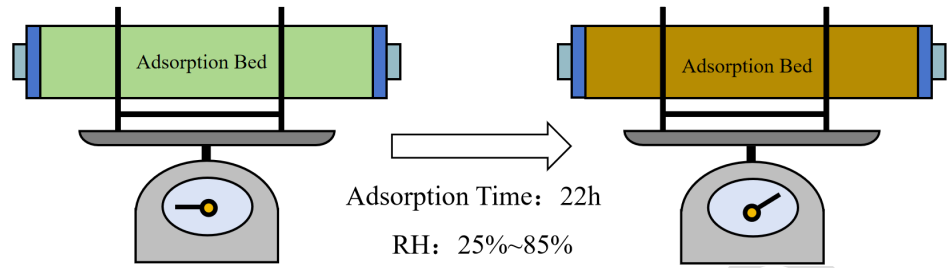


Figure 8. (a) Weigh the adsorption bed before and after each adsorption test

The total mass of water vapor Q adsorbed by the adsorbent bed is calculated using Formula (3-1):

$$Q = 2756.0\text{ g} - 2689.7\text{ g} = 66.3\text{ g} \quad (3-1)$$

The adsorption capacity per unit mass q of the adsorbent material is calculated using Formula (3-2):

$$q = \frac{Q}{m} = 71.8\text{ g} \cdot \text{kg}^{-1} \quad (3-2)$$

The moisture absorption rate $\eta_{\text{moisture absorption}}$ represents the percentage of mass increase of the adsorbent after adsorption, as shown in Formula (3-3):

$$\eta_{\text{hygroscopic}} = \frac{66.3}{922.4} \times 100\% \approx 7.18\% \quad (3-3)$$

That is, the total mass of water vapor Q adsorbed by the adsorbent bed is 66.3 g, the adsorption capacity per unit mass q of the adsorbent material is $71.8\text{ g} \cdot \text{kg}^{-1}$, and the moisture absorption rate $\eta_{\text{moisture absorption}}$ is 7.18%.

3.2. Desorption and Condensation Efficiency

During the desorption phase, the adsorbent bed was heated by the solar vacuum tube collector under natural light conditions. The system temperature rose from $90\text{ }^{\circ}\text{C}$ to $110\text{ }^{\circ}\text{C}$ and was maintained, with desorption lasting for 2 hours. The released water vapor entered the condensation device through pipelines, and after being cooled by fans and fins, it was collected as liquid water. The mass of condensed water measured by the before-and-after weighing method was 51 g.

The condensation efficiency $\eta_{\text{condensation}}$ is defined as the ratio of the mass of condensed water to the total mass of water vapor released during desorption, as shown in Formula (3-4):

$$\eta_{\text{condensation}} = \frac{51}{66.3} \times 100\% = 76.9\% \quad (3-4)$$

That is, the water vapor condensation efficiency is 76.9%.

3.3. Continuous Operation Potential

This experiment presents the adsorption capacity and condensation efficiency of the proposed atmospheric water harvesting device under natural light conditions. The intermittent nature of the device's adsorption-desorption cycle determines that the total time for one system cycle is 24 hours, with the adsorption phase account-

ing for approximately 91.7% and the desorption-condensation phase for approximately 8.3%. The daily water production of this system in the natural environment is 51 g. In the future, the continuous water production performance and system energy efficiency will be further improved through the adjustment and optimal regulation of the units.

4. Conclusions

This study proposes and verifies an integrated atmospheric water harvesting device based on solar vacuum tubes and color-changing silica gel adsorbents. By directly filling the adsorbent bed inside the vacuum tube, the device achieves structural simplification and efficient energy utilization. Under ambient conditions with a relative humidity of 25%-85%, the single-tube adsorbent bed can achieve an adsorption capacity per unit mass of $71.8 \text{ g} \cdot \text{kg}^{-1}$ within 22 hours, demonstrating strong adsorption capacity and environmental adaptability.

The experimental results show that the solar vacuum tube can rapidly heat the adsorbent to 90-110 °C under natural light conditions and stably maintain the desorption process, realizing efficient desorption within 2 hours. The released water vapor is collected by the condensation unit, with a water production capacity of 51 g and a condensation efficiency of 76.9%. The system exhibits excellent thermal response and synergistic characteristics during the adsorption-desorption cycle, verifying the feasibility of the proposed integrated scheme.

The device features compact structure, low operating energy consumption, and modular scalability, indicating application potential in distributed water harvesting in arid and remote areas. Future work will further optimize the condensation and gas path structures, and explore the synergistic operation mechanism of multi-adsorbent bed arrays to achieve continuous day-and-night water production.

References

- [1] Mesfin M. Mekonnen, Arjen Y. Hoekstra, Four billion people facing severe water scarcity. *Sci. Adv.* 2, e1500323 (2016).
- [2] Geng, H. Q., Shi, C. J., & Su, Y. X. (2011). Research progress in air water extraction technology. *Chemical Industry and Engineering Progress*, 30(8), 1664-1672.
- [3] Liu, J. F., Dong, Z. M., Wang, Y., et al. (2023). Application progress of MOFs air water extraction technology. *Water Purification Technology*, 42(2), 47-54.
- [4] Xu W T, Yaghi O M. Metal-organic frameworks for water harvesting from air, anywhere, anytime[J]. *ACS Central Science*, 2020, 6(8): 1348-1354.
- [5] Lapotin A, Kim H, Rao S R, et al. Adsorption-based atmospheric water harvesting: Impact of material and component properties on system-level performance[J]. *Accounts of Chemical Research*, 2019, 52(6): 1588-1597.
- [6] Zhao F, Zhou X Y, Shi Y, et al. Super moisture-absorbent gels for all-weather atmospheric water harvesting[J]. *Advanced Materials*, 2019, 31(10): 1806446.
- [7] Kim, H., Rao, S.R., Kapustin, E.A. et al. Adsorption-based atmospheric water harvesting device for arid climates. *Nat Commun* 9, 1191 (2018).
- [8] Farhad Fathieh et al. ,Practical water production from desert air. *Sci.*

- Adv.4,eaat3198(2018).
- [9] J.Y. Wang, R.Z. Wang, L.W. Wang, J.Y. Liu, A high efficient semi-open system for fresh water production from atmosphere, *Energy*, Volume 138, 2017, Pages 542-551.
 - [10] F.A. Essa, Ammar H. Elsheikh, Ravishankar Sathyamurthy, A. Muthu Manokar, A.W. Kandeal, S. Shanmugan, A.E. Kabeel, Swellam W. Sharshir, Hitesh Panchal, M.M. Younes, Extracting water content from the ambient air in a double-slope half-cylindrical basin solar still using silica gel under Egyptian conditions, *Sustainable Energy Technologies and Assessments*, Volume 39, 2020, 100712.
 - [11] Ahmad K. Sleiti, Hamza Al-Khawaja, Hassan Al-Khawaja, Mohammed Al-Ali, Harvesting water from air using adsorption material - Prototype and experimental results, *Separation and Purification Technology*, Volume 257, 2021, 117921.
 - [12] Wang JY, Wang RZ, Wang LW. Water vapor sorption performance of ACFCaCl₂ and silica gel-CaCl₂ composite adsorbents. *Appl Therm Eng* 2016;100:893-901.
 - [13] Qun Cui, Haijun Chen, Gang Tao, Huqing Yao, Performance study of new adsorbent for solid desiccant cooling, *Energy*, Volume 30, Issues 2 - 4, 2005, Pages 273-279.
 - [14] Zheng X, Ge TS, Hu LM, Wang RZ. Development and characterization of mesoporous silicate-LiCl composite desiccants for solid desiccant cooling systems. *Ind Eng Chem Res* 2015;54(11):2966-2973.
 - [15] Zheng X, Ge TS, Wang RZ. Recent progress on desiccant materials for solid desiccant cooling systems. *Energy* 2014;74:280-294.
 - [16] Yu N, Wang RZ, Lu ZS, Wang LW. Development and characterization of silica gel-LiCl composite sorbents for thermal energy storage. *Chem Eng Sci* 2014;111:73-84.
 - [17] Bui DT, Nida A, Ng Kim C, Chua Kian J. Water vapor permeation and dehumidification performance of poly(vinyl alcohol)/lithium chloride composite membranes. *J Membr Sci* 2016;498:254-262.
 - [18] Aristov YI, Tokarev MM, Cacciola G, Restuccia G. Selective water sorbents for multiple applications, 1. CaCl₂ confined in mesopores of silica gel: sorption properties. *React Kinet Catal Lett* 1996;59(2):325-333.
 - [19] Aristov YI, Tokarev MM, Restuccia G, Cacciola G. Selective water sorbents for multiple applications, 2. CaCl₂ confined in micropores of silica gel. *React Kinet Catal Lett* 1996;59:335-342.
 - [20] Gordeeva LG, Restuccia G, Cacciola G, Aristov YI. Selective water sorbents for multiple applications, 5. LiBr confined in mesopores of silica gel: sorption properties. *React Kinet Catal Lett* 1998;63(1):81-88.
 - [21] Aristov YI, Glaznev IS, Freni A, Restuccia G. Kinetics of water sorption on SWS-1L (calcium chloride confined to mesoporous silica gel): influence of grain size and temperature. *Chem Eng Sci* 2006;61(5):1453-58.
 - [22] Aristov YI. Challenging offers of material science for adsorption heat transformation: a review. *Appl Therm Eng* 2013;50(2):1610-1618.
 - [23] Aristov YI, Tokarev MM, Gordeeva LG, Snytnikov VN, Parmon VN. New composite sorbents for solar-driven technology of fresh water production from the atmosphere. *Sol Energy* 1999;66(2):165-168.
 - [24] Ji JG, Wang RZ, Li LX. New composite adsorbent for solar-driven fresh water production from the atmosphere. *Desalination* 2007;212(1-3):176-182.
 - [25] Gad HE, Hamed AM, El-Sharkawy II. Application of a solar desiccant/collector system for water recovery from atmospheric air. *Renew Energy* 2001;22:541-556.
 - [26] J.Y. Wang, R.Z. Wang, Y.D. Tu, L.W. Wang, Universal scalable sorption-based atmosphere water harvesting, *Energy*, Volume 165, Part A, 2018, Pages 387-395.