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# Review of solid/liquid desiccant in the drying applications and its regeneration methods

S. Misha[a,b,*], S. Mat[a], M.H. Ruslan[a], K. Sopian[a]

[a] Solar Energy Research Institute, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
[b] Department of Thermal-Fluids, Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

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Desiccant material has been used in drying applications because of its low energy consumption, among other advantages. Desiccant material can produce hot and dry air that is beneficial for the drying process. The advantages of using desiccant material in a drying system include continuous drying even during off-sunshine hours, increased drying rate due to hot and dry air, more uniform drying, and increased product quality especially for heat-sensitive products. Some problems in desiccant system such as pressure drop in solid desiccant, carry over of liquid desiccant by air stream and low moisture adsorption capacity may be improved by optimization of the design of desiccant system. Numerous researchers have studied the low cost and low regeneration temperature of desiccant material, and the optimization of desiccant application to produce more competitive energy. The use of heat to regenerate desiccant material in a drying system has limitations in energy saving. However the use of low energy or free available energy such as solar energy and waste heat from industrial processes for regeneration of desiccant material will make the system more cost-effective. This paper presents several works on the regenerative method of the desiccant system and its application in the drying system for both solid and liquid desiccant materials.

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## 1. Introduction

Drying is a heat and mass transfer process to remove water or another solvent by evaporation from a solid, semi-solid, or liquid. Normally, hot air stream is applied to dry any product, and the

* Corresponding author at: Department of Thermal-Fluids, Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia. Tel.: +60 6 2346712; fax: +6 06 2346884
*E-mail address:* suhaimimisha@utem.edu.my (S. Misha).

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solvent to be removed is almost invariably water. The drying curve is used to determine the drying rate. The drying curve presents the average moisture content of the product as a function of time. The drying process contributes approximately 12% of the total energy used in industrial sectors worldwide. The rise in fuel prices increases the energy costs for the drying process and reduces the profit margins of industries involved in drying.

Usually the drying process is divided into two phases [1]. In phase I, the inside and surface of the product have the same moisture content initially. The surface will be saturated with vapor when it is heated by hot air, and then the water will evaporate. In phase II, when the surface of the product has dried up, water from the interior will migrate to the surface and then evaporate. In this phase, the energy required is much more important than in the first phase. However some products do not present phase 1 and phase 2. Belessiotis and Delyannis [2] defined another phase, phase III, for hygroscopic products where the moisture content continues to decrease until equilibrium is achieved. However, most products stop drying before this phase. Drying time depends on the nature of the product and the drying conditions.

Important parameters in the drying process are humidity, temperature, and air flow rate. Some products like food, pharmaceutical products, and others heat-sensitive products are not suitable for drying at high temperature because product quality may be degraded or damaged. Drying using desiccant material produces dry air because the desiccant material adsorbs moisture from the air. The processed air produced after dehumidification is not only dry, but the temperature also increases due to the isothermal process. Drying at low temperature and humidity can only be carried out using a desiccant, which can maintain the fresh color of food [3–5]. Other drying methods can only produce low humidity of air at high temperature. Using a different drying process, the same product showed significant effects in texture, color, and nutrient content [6].

Desiccants work based on the principle of moisture transfer due to the difference of vapor pressure between the air and the desiccant [7]. The cool desiccant with low moisture content will adsorb moisture from air until its vapor pressure is in equilibrium with the air. The desiccant must be heated so that the vapor pressure on the desiccant surface is higher than the surrounding air, enabling the desiccant to remove the moisture. The application of a desiccant is considered as renewable energy, but the regeneration process can be carried out by renewable or non-renewable energy. Some studies have been done on custom-made proprietary desiccants with lower regeneration temperatures. With low regeneration temperature, solar energy and waste heat from any system may be used.

Several parameters are measured and reported to describe the dryer. Leon et al. [8] listed parameters generally presented to evaluate solar dryers. The parameters include physical features of the dryer, thermal performance, quality of dried product, cost of dryer and payback period. These parameters are also suitable for any dryer system. If the desiccant material is used in the dryer system, the effectiveness of dehumidification and regeneration is introduced as an additional parameter. Desiccant materials can be liquid or solid. For liquid desiccants, absorption is performed by a deliquescent material such as calcium chloride ($CaCl_2$) and lithium chloride, while solid desiccant can be either polymer sorbent [9] or a porous material such as silica gel, alumina silicate, and zeolite [10,11].

Atuonwu et al. [12] developed mathematical models to investigate the energy efficiencies of conventional dryer, adsorption dryer, condensation dryer, and heat pump dryer at the same operating temperature. The schematic diagrams of each drying process are shown in Fig. 1. Optimization of the important design and operational parameters for each dryer type produces better product quality with the same efficiency as a conventional dryer, and improves energy efficiency while achieving the same product quality. Desiccant dehumidification systems have the advantage of utilizing heat integration. Additionally, with the same energy consumption, dehumidification dryers produce better product quality. Adsorption dryers and heat pumps show better efficiency and product quality compared to other dryers.

Enteria and Mizutani [13] proposed the classification of the desiccant-based air dehumidification and cooling system as shown in Fig. 2. The selection of desiccant materials depends on the cost, the operating conditions, and the source of thermal energy [14]. The hybrid-based system is the combination of solid or liquid desiccant materials, and the vapor compression system cools the air and regenerates the desiccant. This classification helps to differentiate the types of desiccants used in cooling technologies.

## 2. Types of desiccant dryer

Desiccant materials can be liquid or solid type. Each type has its advantages and disadvantages. The best desiccant material has a high adsorption capacity for all ranges of relative humidity (humidification process) and can be regenerated at low temperature. The type of desiccant selected will depend on the intended application.

### 2.1. Solid desiccant drying system

Solid desiccants cause a pressure drop in the processed air when it passes through the desiccant material. In general, using liquid desiccant in the construction of a dryer is more complicated than using solid desiccant because handling solid desiccant material is easier. Solid desiccant systems are normally in the form of stationary or rotary wheel beds for packing the desiccant materials.

Jeong et al. [15] used validated simulation models to study the performances of a conventional desiccant system (wheel and batch type), a system with a precooler, double-stage systems (two desiccant wheels and a four-partition desiccant wheel type), and a batch system with an internal heat exchanger. The study investigated the effect of heated and cooled air temperature on various parameters using the trial-and-error optimization method. The batch system with the internal heat exchanger (Fig. 3) was found capable of operating at the lowest heated air temperature around 33 °C and at a cooled air temperature of 18 °C.

Thoruwa et al. [16] constructed a solar dryer system integrated with desiccant material to dry fresh maize. A flat plate solar air heater was connected to the drying chamber and the solid desiccant material was mounted above the maize bed (Fig. 4). Bentonite clay and $CaCl_2$ materials were selected as desiccant material due to their low cost and high moisture sorption. The desiccant had a moisture sorption of 45% (dwb) and could be regenerated at 45 °C. The drying process took place at daytime using solar heated air; at nighttime, drying occurred using forced air circulation throughout the desiccant bed. The saturated desiccant bed was regenerated by solar energy during daytime. The dryer could dry 90 kg of fresh maize from 38% to 15% (dwb) within 24 h.

Thoruwa et al. [17] developed low-cost solar regenerative solid clay–$CaCl_2$-based desiccants to continue the drying at nighttime. Moisture sorption and desorption performance of the desiccants were under the same solar drying system condition at 85% (RH) and 25 °C for 120 h for dehumidification, and 50 °C and 20% (RH) for 8 h for regeneration. The compositions of the desiccants are given by percentage of mass. The bentonite–$CaCl_2$ (type 1: 60% bentonite, 10% $CaCl_2$, 20% vermiculite, and 10% cement) desiccant has a maximum moisture sorption of 45% (dwb). The moisture sorption of Bentonite $CaCl_2$ (type 2: 65% bentonite, 5% $CaCl_2$, 20%

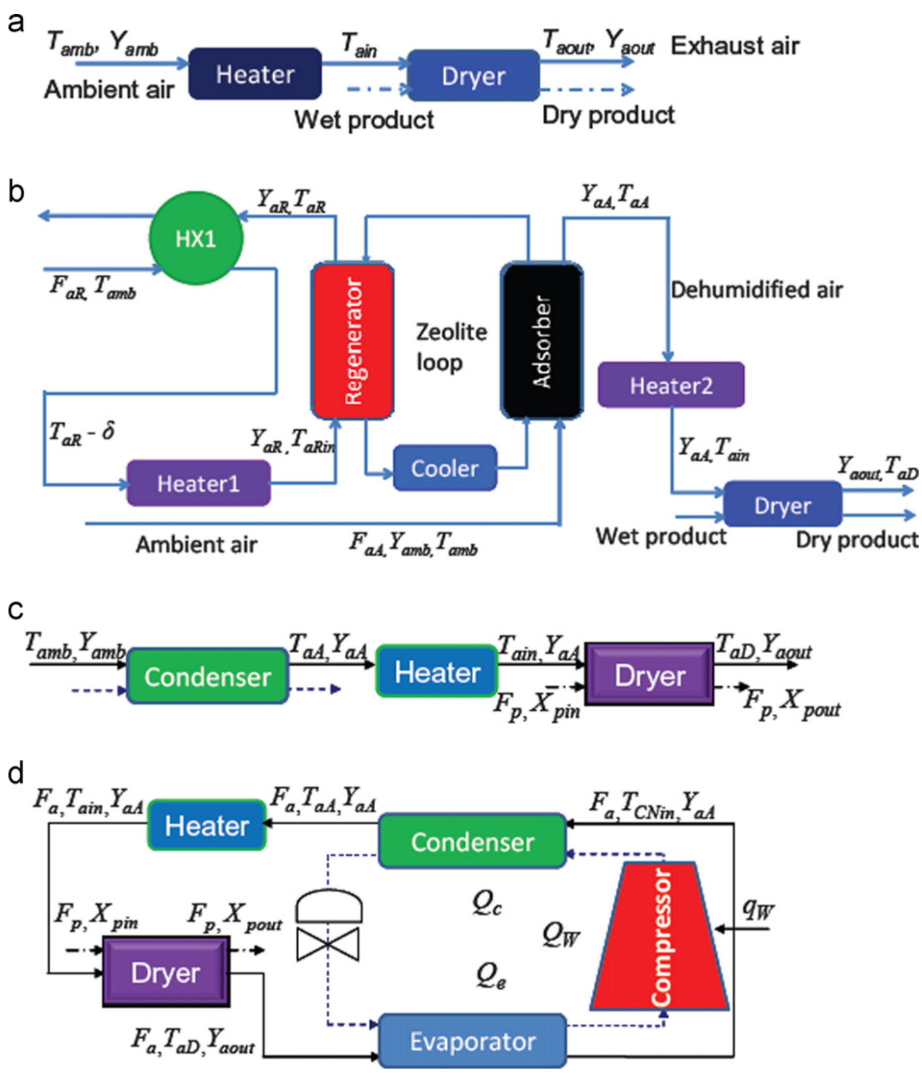


**Fig. 1.** Schematics of dryer types [12]. (a) Conventional dryer, (b) adsorption drying process, (c) condensation dryer and (d) heat pump dryer.

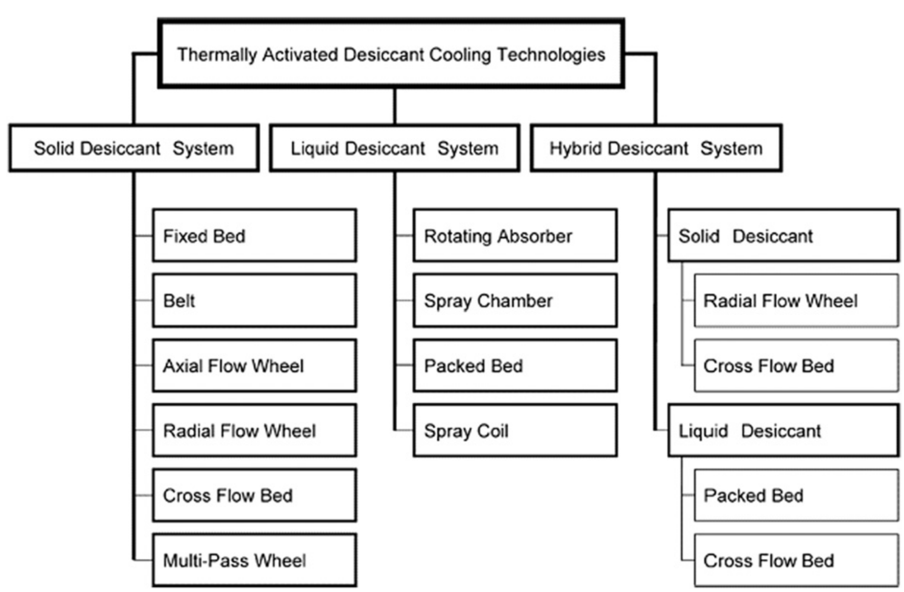


**Fig. 2.** Classifications desiccant cooling [13].

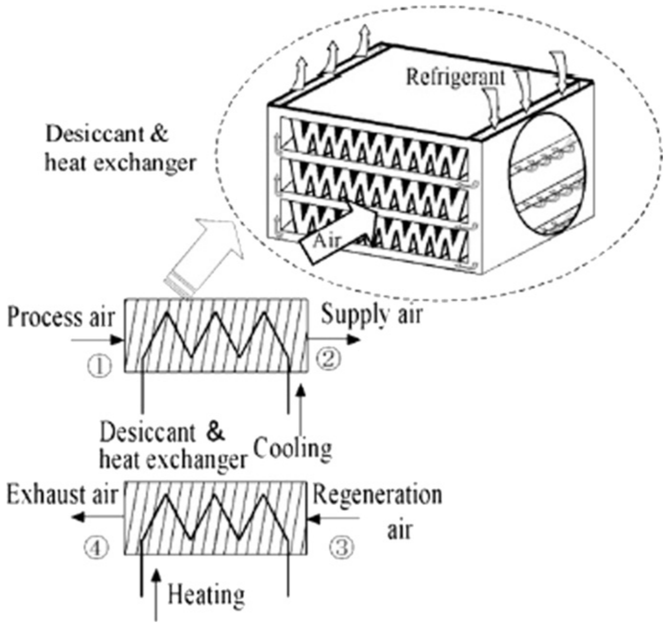


**Fig. 3.** Batch-type system with internal heat exchanger [15].

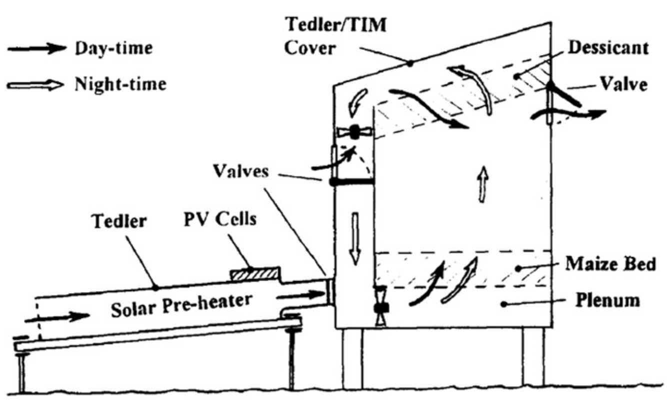


**Fig. 4.** Operation of solar-desiccant dryer [16].

vermiculite, and 10% cement) and kaolinite–$CaCl_2$ (type 3: 65% kaolinite, 5% $CaCl_2$, 20% vermiculite, and 10% cement) desiccants are the same with values of 30% (dwb).

Shanmugam and Natarajan [18] developed forced convection and desiccant integrated solar dryer (Fig. 5) to investigate its performance. Bentonite–$CaCl_2$ (type 1) was used as a desiccant to continue the drying operation during off-sunshine hours, during which air inside the drying chamber was circulated through the desiccant bed by a two-way fan. During hot weather, a flat plate collector heated the air, and a blower forced the hot air into the drying chamber. At the same time, solar radiation regenerated the desiccant bed. Results showed that desiccant drying produces more uniform drying and improves the quality of the dried product. The characteristic and structural integrity of the desiccant remained stable even after a year. The reflective mirror was used to concentrate the solar radiation on the desiccant bed [19]. The reflective mirror improved the drying performance of the desiccant by 20% and decreases drying time by 4 h and 2 h for pineapple and green peas, respectively. Generally, in all experiments, 60% of moisture in the product was removed by hot air stream and another 40% by the desiccant.

Hodali and Bougard [20] designed an adsorption unit of silica gel integrated in a tunnel-type crop solar dryer (Fig. 6). The proposed solar drying was a coupling of collector–adsorber–dryer in a series. This system was numerically simulated to optimize the physical and operational parameters. Optimal lengths of the collector, adsorber, and dryer are 10, 1.5, and 10 m, respectively, with 10 cm height and 2 m width. The heat of desorption supplied to the desiccant during the day is rejected to the air during the night adsorption. During the night, the drying rate is higher at the dryer entrance due to the relatively dry and warm air supplied by the adsorber. While during the day, the drying is more efficient near the exit of the dryer due to the higher temperature of apricots as we move along the dryer. This drying system reduced the drying time by about 8 h and improved the quality of the dried product.

Nagaya et al. [21] designed and developed a desiccant-based low temperature drying system (Fig. 7) to dry vegetables. The drying system was equipped with heating and air circulation control to maintain a constant temperature of 49 °C. Experiment results showed that drying vegetables using this technique

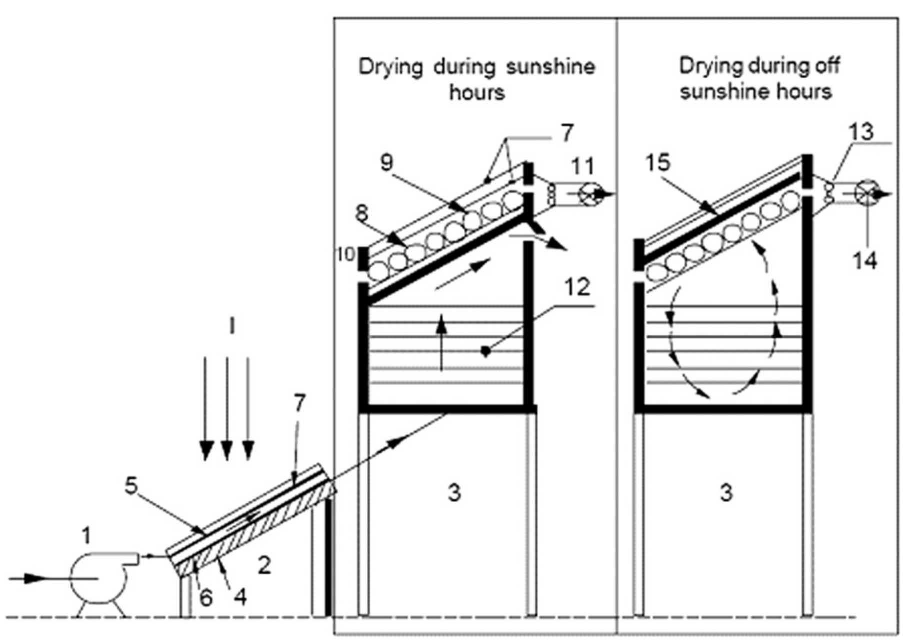


**Fig. 5.** Desiccant integrated solar dryer [18]. 1—Blower; 2—flat plate collector; 3—drying chamber; 4—insulator; 5—absorber plate; 6—bottom plate; 7—transparent cover; 8—desiccant bed; 9—plywood; 10—air inlet; 11—duct for air exit; 12—trays; 13—two-way fan; 14—valve; 15—plywood.

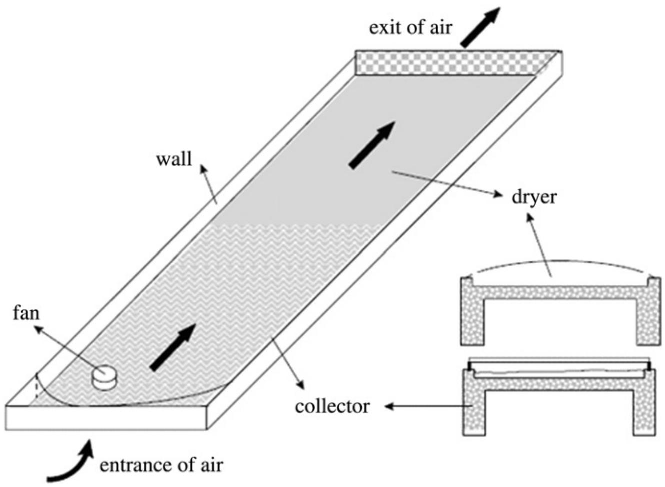


**Fig. 6.** Tunnel type dryer [20].

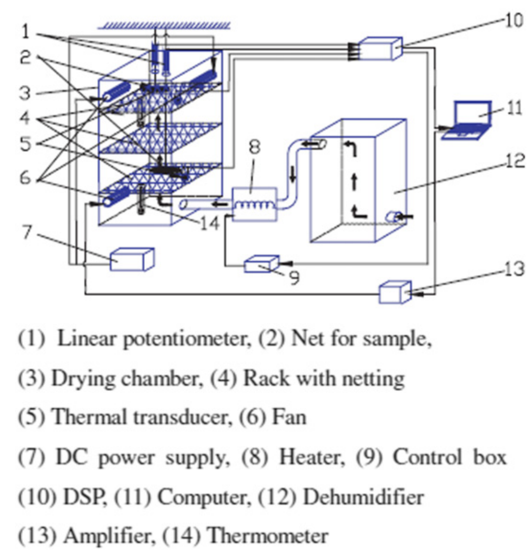


**Fig. 7.** Desiccant drying system with controlled temperature and air flow [21].

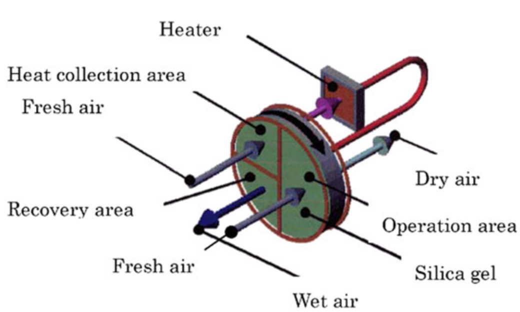


**Fig. 8.** Desiccant drying rotor [21].

produce good product uniformity and maintain their fresh color, original texture and shape, and high vitamin content. The drying rate of this system is six times faster than that of conventional desiccant drying and up to 12 times faster than open sun-drying. The desiccant-rotor dehumidifier is divided into three zones (Fig. 8). An operating zone in which the silica gel captures moisture from the air (supplying dry air to the drying chamber), a recovery zone in which wet air is heated and blown out and a heat collection zone in which the silica gel releases heat to external fresh air.

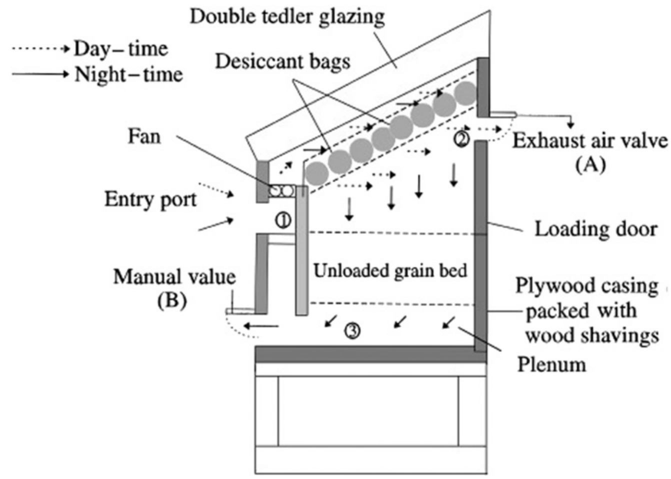


**Fig. 9.** Integrated desiccant/collector dehumidifier [22].

Thoruwa et al. [22] built and tested a prototype dryer that provides dehumidified air at night using solid bentonite $CaCl_2$ as a desiccant material (Fig. 9). A photovoltaic panel and a 12 V battery were used to power a small electric fan and produce constant air flow. The collector area of 0.921 $m^2$ containing 32.5 kg of desiccant could produce an air flow of 2 $m^3$/min throughout the night. The relative humidity of dehumidified air was about 40% below ambient level and temperature increased by 4 °C. The desiccant was regenerated by solar radiation during the daytime. The system could capture and use more than 50% of the incident solar energy.

Madhiyanon et al. [23] developed a hot-air drying system integrated with a rotary desiccant wheel (Fig. 10) to dry coarsely chopped coconut pieces. The dryer consists of two air circuits. The first air circuit dries the product and operates in closed-system or partially open-system modes. The second air circuit regenerates the desiccant. Ambient air needs to be dehumidified through the adsorption section of the desiccant wheel, while heated air from the second air circuit regenerates the saturated desiccant to remove moisture. A 150 W and a 0.5 hp blower were used to supply air for regenerating the silica gel and drying the product, respectively. Two separate 1 kW electrical heaters heated the air for drying and regeneration. Drying time for the integrated system was reduced by about 25% compared with the pure hot-air system due to the decreased humidity of the drying air. However, the energy used by the combined system was 40% to 80% higher than that used by the pure hot-air system. The portion of energy required in regeneration was about 40% of the total energy used. The relative humidity (RH) of the inlet drying had a significant effect on the color of the dried coconut pieces.

Punlek et al. [24] studied, simulated, and conducted experiments on hybrid PV/T assisted desiccant integrated HA-IR drying system (HPIRD), as shown in Fig. 11. The system mainly consists of a PV air collector (PVAC), a desiccant silica gel bed (DB), and a drying chamber with infrared. The PVAC generates electricity and acts as a solar collector. Electricity is used to operate the fan in the drying chamber. There are two types of PVAC designs: single-pass air channel ($PVAC_A$) and a design modified with a rectangular fin ($PVAC_{AF}$), as shown in Fig. 12. The results showed that the $PVAC_{AF}$ systems increased the thermal efficiency and electrical efficiency in comparison to the $PVAC_A$ system. The fins were more effective in enhancing the heat transfer from the channel wall to the air flowing in the channel. The effect of the three DB shapes on moisture absorption was investigated (Fig. 13). The simulation of air flow rate and pressure drop through the DB shapes was done using CFX program. The prediction and results showed that the v-shape DBs were the best models for use in drying test. The drying

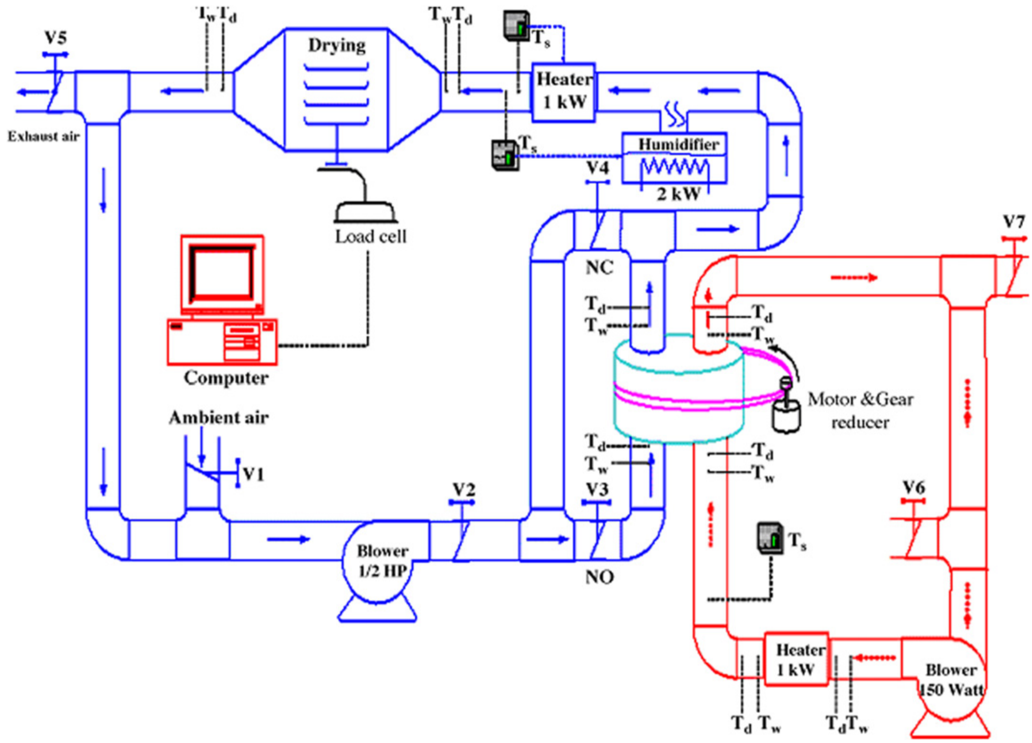


Fig. 10. Hot-air dryer integrated with rotary desiccant wheel [23].

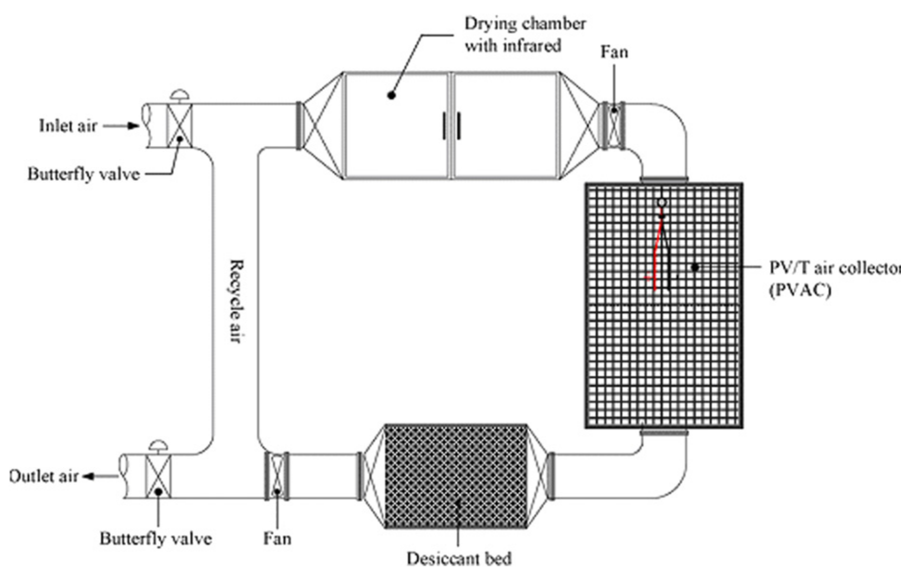


Fig. 11. Hybrid PV/T-desiccant integrated with infrared drying system (HPIRD) [24].

chamber was also designed to dry agricultural products using hot air combined with infrared (HA-IR). A black ceramic IR heater with 800 W was used as the infrared heat source and an electrical heater was used to heat up drying air. The performance of HPIRD drying test at a temperature of 60 °C and a velocity of 0.6 m/s reduced the drying time by 44% and consumed 63% less energy compared with hot air drying. The hybrid system also produced better quality of dried product compared with hot air infrared drying.

Chua and Chou [25] categorized desiccant drying as one of the low-cost drying methods for developing countries, including fluidized bed, spouted bed, solar, infrared, and convective dryer. The methods were selected based on the following considerations: (1) low initial capital cost; (2) system is easy to construct, operate, and maintain; and (3) high drying speed and capable of producing better product quality than open sun-drying. The desiccant method has the following main advantages: (1) saturated desiccant can be regenerated by hot air stream; (2) system is easy to design and no required operation maintenance for several years; (3) integrating the desiccant with other drying systems will reduce energy consumption; and (4) replacing the desiccant material after cycles of operations is easy.

### 2.2. Liquid desiccant drying system

One drawback of the liquid desiccant is that it is carried over by air stream during the dehumidification and regeneration

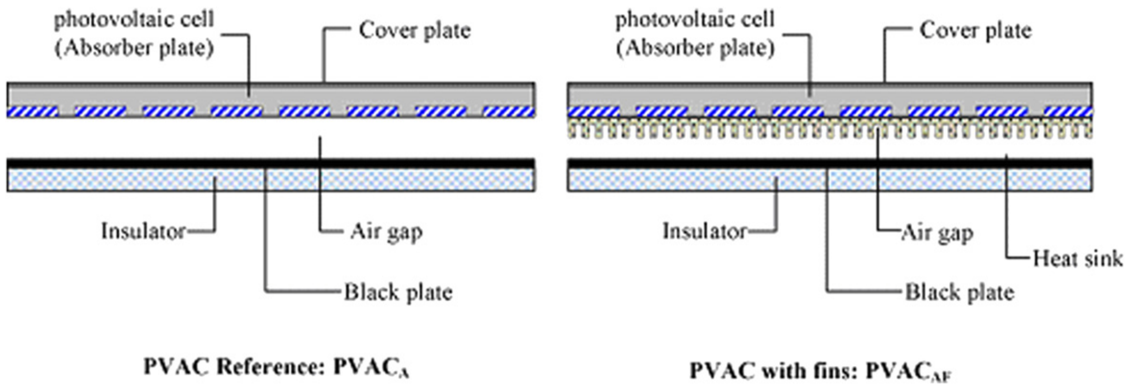


**Fig. 12.** Cross section view of PV/T air collector (PVAC) [24].

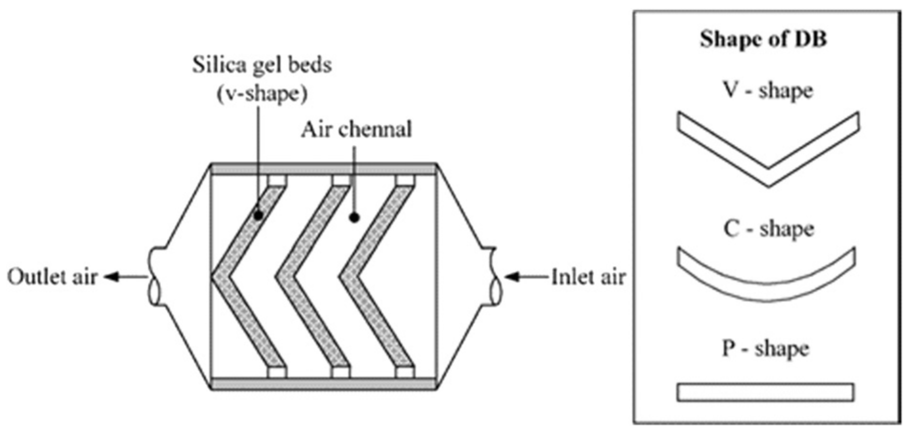


**Fig. 13.** Shapes of silica gel desiccant bed [24].

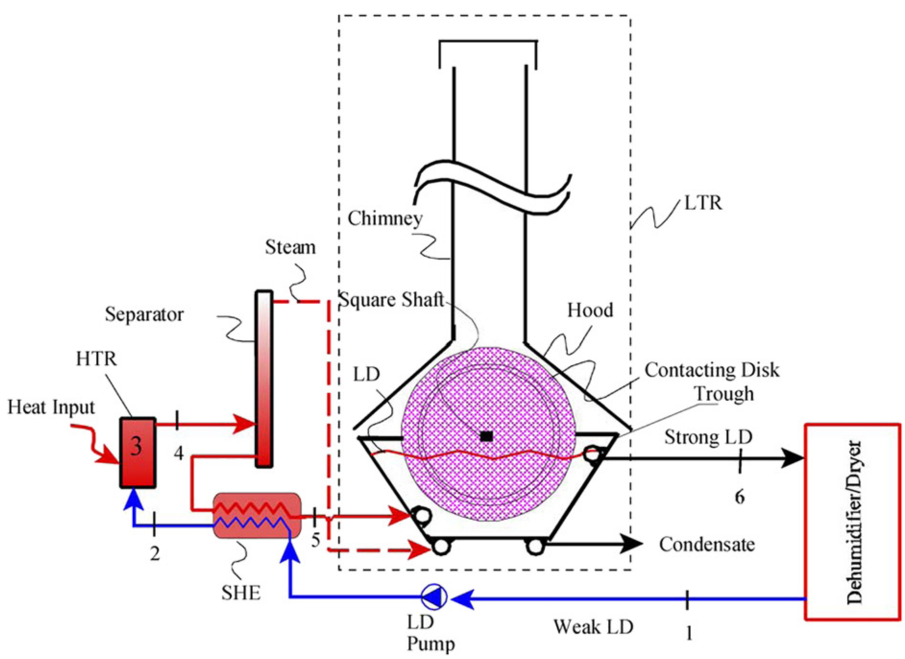


**Fig. 14.** LDBD with two-stage regenerator [27].

process. However, proper dehumidifier and regenerator design will reduce or eliminate this problem. Generally, using liquid desiccant to construct a dryer is more complicated than using solid desiccant. However, a liquid desiccant system is flexible and can position the regeneration area far away from the dehumidification zone, allowing localized dehumidification. The advantage of the liquid desiccant is that regeneration can be done at a lower temperature with high moisture removal capacity. Liquid desiccant can also absorb organic and inorganic contaminants from the air [26].

Rane et al. [27] developed liquid desiccant-based dryer (LDBD) with higher energy efficiency. A $CaCl_2$ solution was used as liquid desiccant. The contacting device was used to transfer the moisture in the absorber and regenerator. Compared to conventional packing, the surface density of the contacting device was about 120% to 185% higher. The regeneration process is divided into two stages (Fig. 14). First, the dilute liquid desiccant is heated by an external heat source, boiled in the high temperature regenerator (HTR), and then the steam and liquid desiccant mixture are separated in the separator. Second, the hot liquid desiccant flows through the tube to the low temperature generator (LTR) and condenses. The water from the dilute liquid desiccant at contacting disks is transferred to the air due to the vapor pressure difference between the liquid desiccant and the air. There are 70 units of contacting disks rotated at 3–5 rpm. A chimney helps circulate the air by the buoyancy force for moisture removal.

The complete LDBD setup is shown in Fig. 15. The concentrated liquid desiccant from the trough of LTR flows to the dehumidifier by gravity. The construction of the dehumidifier is similar to the LTR, but in this case, water from the air is transferred to the liquid desiccant in the contacting disk. The dehumidified air flows to the drying section to remove moisture from the products in the drying chamber. The processed air then passes through four dehumidifiers in a closed loop system, which will not be affected by ambient conditions. The dilute liquid desiccant from the dehumidifier flows to the reservoir by gravity. Then, the liquid desiccant from the reservoir moves to HTR by pump for the regeneration process, and the cycle is repeated. The dryer was designed to dry the paper tray. The carryover of liquid desiccant by air stream was eliminated. Specific moisture extraction rate (SMER) and energy savings were 227% and 56%, respectively, compared with the hot air-based drying system.

The liquid desiccant drying method has been used in drying green gelcast ceramic parts to shorten the drying time and to avoid defects due to the release of residual stresses. Barati et al. [28] studied the kinetics of one-dimensional drying of green gelcast ceramic parts using the Fickian model. Results showed that higher ceramic loading, higher sample thickness, and lower concentration of the liquid desiccant solution decrease the drying rate. Experiments have been done involving the immersion of green gelcast parts in an aqueous or non-aqueous solution of PEG1000 as liquid desiccant [29]. Cracking, bending, and warping, which are the common defects during conventional drying methods, are eliminated using this method, and drying time is reduced about 10 times. An aqueous solution of the liquid desiccant can achieve more homogeneous drying. However, drying rate in an aqueous solution of PEG1000 is lower than that of a non-aqueous solution.

Trunec [30] conducted osmotic drying of gelcast alumina in water solutions of polyethylene glycol (PEG) with different molecular weights in the range of 1000–80,000 g/mol. The PEG solution with highest molecular weight was the most efficient liquid desiccant. Up to 30% water content from gelcast bodies immersed in a 43 wt% solution of PEG80000 can be removed. Uniform and crack-free drying can be achieved by optimized osmotic drying in the PEG solution with a high molecular weight.

Zheng et al. [31] used the liquid desiccant method for drying $BaTiO_3$-based semiconducting ceramic gelcast parts. The gelcast parts were immersed in the liquid desiccant. The removal of water from the gelcast parts was due to the osmotic difference between the liquid desiccant and the gelled polymer in the part. Results showed that increasing the loading of green gelcast parts to more than 45 vol% will reduce the stresses developed during drying, and a higher concentration of the liquid desiccant will not induce any defects and will produce a smooth surface ceramic. However, the part with lower thickness and higher solid content in the gel will increase the ceramic density. The gelcast parts can be dried safely at room conditions or in an oven just after the critical stage of drying process in liquid desiccant.

The solid desiccant is more widely used in drying applications compared to liquid desiccant. This is because the solid desiccant required simple construction of drying system. Most of the solid desiccant is designed in the form of rotary wheel beds. However, liquid desiccant has low regeneration temperature with high moisture removal capacity compared to solid desiccant. Some advantages of using desiccant material in a drying system include continuous drying even during off-sunshine hours, increased drying rate due to hot and dry air, more uniform drying, and increased product quality especially for heat-sensitive products.

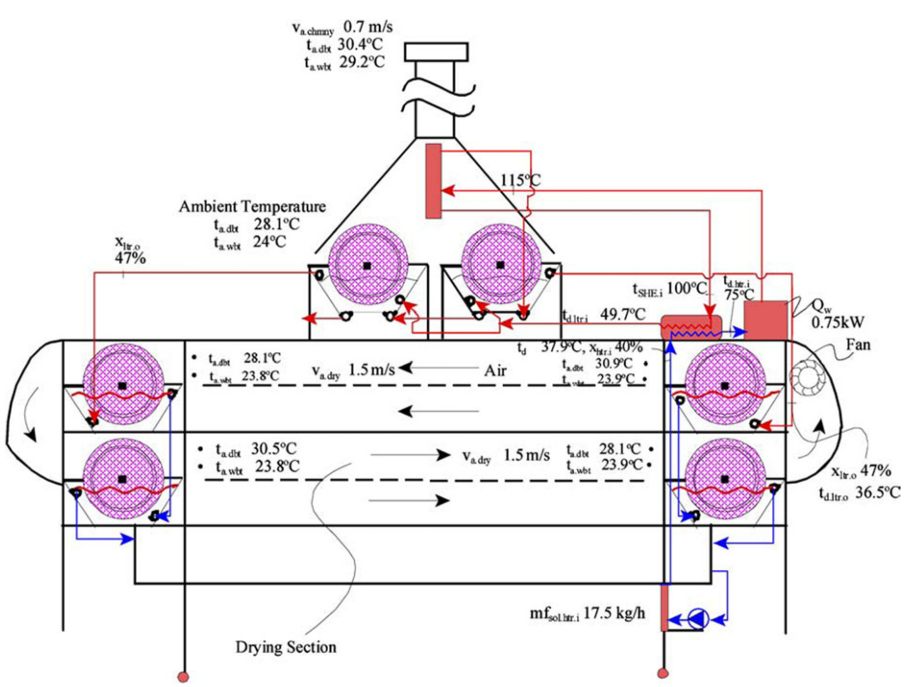


**Fig. 15.** Complete setup of LDBD [27].

## 3. Regeneration method of desiccant system

Regeneration of the desiccant material at low temperature will give more benefits in terms of energy efficiency. The use of renewable energy or waste heat from any system will also reduce the operation cost of the desiccant system. Common regeneration methods use solar energy, electrical heater, and waste heat. Some studies conducted used other regeneration

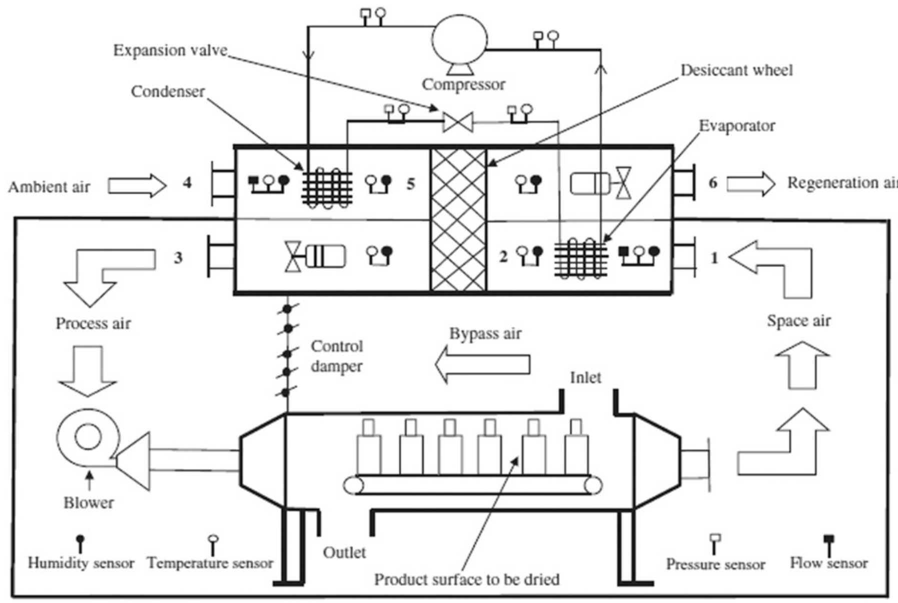


**Fig. 16.** Hybrid desiccant system [32].

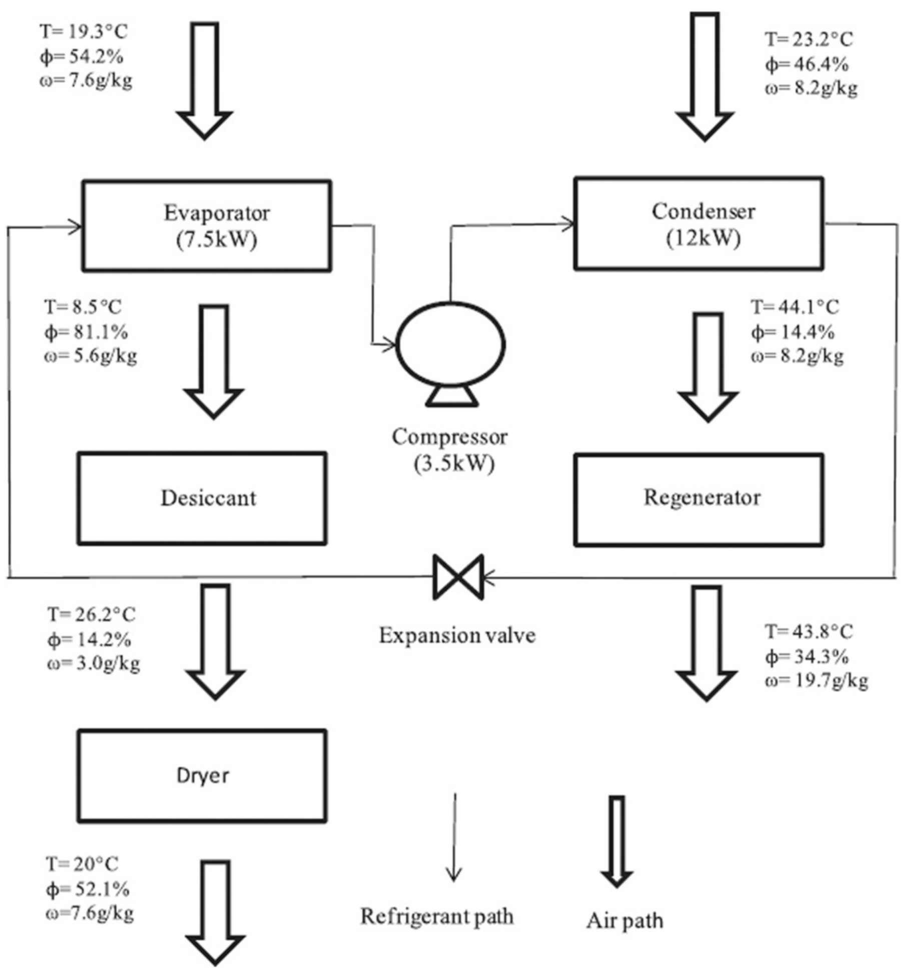


**Fig. 17.** Hybrid system drying air process [32].

methods to identify the most effective and economical method.

### 3.1. Vapor compression system (heat pump)

Heat pump is categorized as an energy-efficient dryer system due to its low energy consumption. The combination of heat pump system and desiccant system in drying application improves energy efficiency and produces lower humidity of the processed air. This system is also called the hybrid desiccant system. Heat released by the heat pump through the condenser can be used to regenerate the desiccant materials. An evaporator and a desiccant material can carry out the dehumidification process to produce processed air with better condition at low energy consumption.

Wang et al. [32] designed and developed a hybrid system combining heat pump and desiccant wheel (Fig. 16) to produce low-cost drying and supply low dew-point temperatures (DPT) conditions of air. This system is used for rapid surface drying to avoid re-condensation at low DPT and low dry ball temperatures (DBT) in the range of $-10\,^{\circ}\mathrm{C}$ to $-20\,^{\circ}\mathrm{C}$ and $20\,^{\circ}\mathrm{C}$ to $30\,^{\circ}\mathrm{C}$, respectively, after a product is dried. The heat dissipated by the condenser regenerates the desiccant wheel. Moisture from the ambient air is removed in a dehumidification process by condensation from an evaporator and adsorption using a solid desiccant to produce dried air. The schematic diagram and sample of data for the hybrid systems are shown in Fig. 17. This system is capable of saving heat energy of up to 30–60% compared with a single heat pump or desiccant wheel. The desiccant wheel in this system improves the SMER by 12–20%.

### 3.2. Solar energy

The use of solar energy for the regeneration process of desiccant material has been studied extensively because it is a free energy source. The initial cost of solar energy is quite expensive, but in the long run, it can contribute to savings in overall cost. Therefore, the payback period should be considered. However, solar radiation is weather-dependent; therefore, back-up energy or energy storage is required to continue the drying process when solar energy is not available.

Lu et al. [33] developed two solar desiccant dehumidification regeneration systems known as SDERC and SRAD. The SDERC system mainly consists of a glazed metal chamber, a solid-desiccant bed, three separate axial flow fans, a brass radiation cooling duct, a three-way valve mechanism, and an evaporative cooler. The assembly of the SDERC system is depicted in Fig. 18. At nighttime, indoor air flows through the solid desiccant bed and then through an evaporative cooler to decrease the temperature before it reenters the house. During daytime, solar energy heats the glazed chamber and air passes through the saturated desiccant for the regeneration process. In a SRAD system, the construction of the air ventilation system and the construction of the desiccant bed are different. The design of an SRAD desiccant bed is shown in Fig. 19. In desiccant bed areas I and III, the silica gel particles adhere to the surface of the metal plate and a nearly zero pressure drop is observed when the processed air passes through these areas. For areas II and IV, the solid desiccant particles fully occupied the 2 cm gap between the metal and the glaze. Both systems are simple and cost-effective compared to conventional electric dehumidifiers.

Ahmed et al. [34] constructed an open test loop for the desiccant wheel (Fig. 20) to conduct experiments and thus validate the numerical model. Heat and mass transfer for the adsorption and desorption of the desiccant wheel were investigated. The

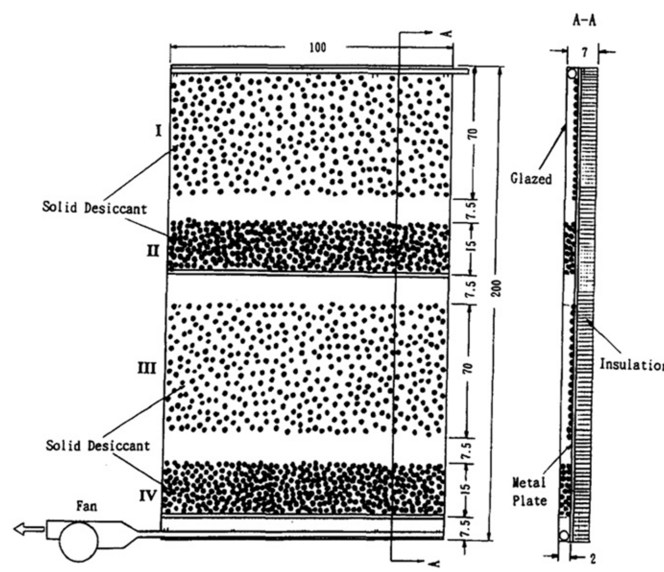


**Fig. 19.** Desiccant bed of SRAD system [33].

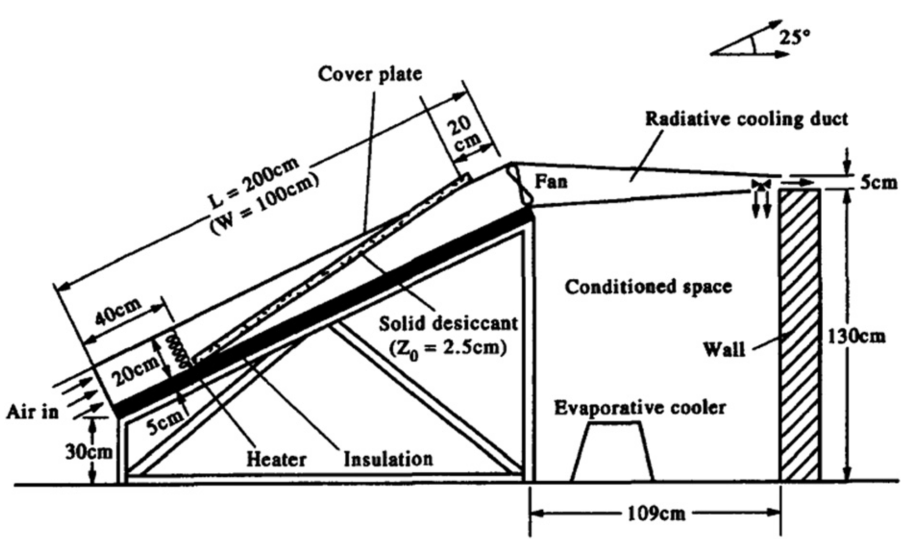


**Fig. 18.** Installation of SDERC system [33].

simulation result showed that, for temperatures between 60 °C and 90 °C, the effective wheel thickness was in the range of 0.18–0.26 m, air flow rate was 1–5 kg/min, and wheel speed was between 15 and 60 rev/h. The performance curves of the wheel for each wheel thickness were found to have an optimum value for wheel speed.

Xiong et al. [35] studied a two-stage solar-powered liquid desiccant dehumidification system with two types of desiccant solutions (Fig. 21). Air moisture was removed by a pre-dehumidifier and a main dehumidifier using $CaCl_2$ and lithium bromide (LiBr). The inter-cooling effect occurred between the two dehumidification stages through an air-to-air heat exchanger. Desiccant storage capacity was analyzed by variations in the desiccant concentration. The pre-dehumidification using a $CaCl_2$ solution gave a significant effect in high ambient humidity. The desiccant investment can be decreased by 53%, with the thermal coefficient of performance ($T_{cop}$) and the coefficient of performance (COP) of 0.97 and 2.13, respectively.

Alosaimy and Hamed [36] developed and investigated the application of a flat plate solar water heater to regenerate the liquid desiccant. The main components of the system are a solar water heater with a storage tank, a water-to-air heat exchanger, and a packing of a honeycomb type as shown in Fig. 22. The water was heated by solar energy through the solar water collector. Then the hot water in the tank was circulated in a heat exchanger by a pump. Hot air from the heat exchanger was blown to the packing for the regeneration of $CaCl_2$ solution. Experimental results showed that solar energy can regenerate up to 50% of the solution at 30% solution concentration.

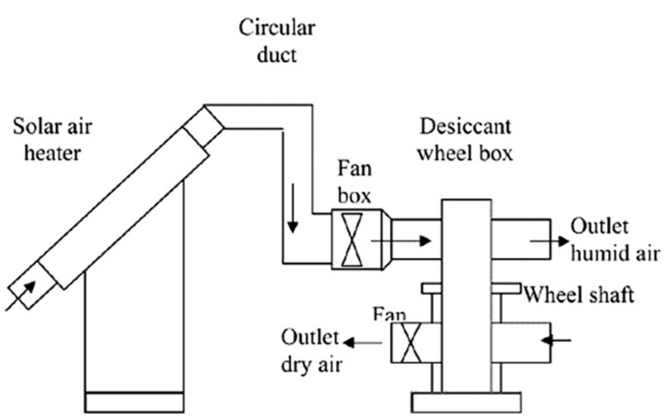


**Fig. 20.** Test loop for the desiccant wheel [34].

### 3.3. Electrical heater

An electrical heater is a simple application that exhibits regeneration of desiccant material and is also a consistent heat source. However, the main drawback of electrical heaters is their high energy consumption. Due to its high operating cost, sometimes the electrical heater is only used as a back-up energy source if solar energy or waste heat is not available or is not enough.

Mandegari and Pahlavanzadeh [37] introduced a novel efficiency definition for a desiccant wheel by comparing the process of air enthalpy between outlet and inlet. The experimental setup is shown in Fig. 23, where the heater is used to regenerate the desiccant wheel and to control the process of air conditioning. In some situations, the adiabatic efficiency will have an optimum value that depends on dehumidification and regeneration efficiency. All the efficiencies, except adiabatic efficiency, increase when the desiccant wheel speed is increased from 4 rev/h to 24 rev/h.

Bassuoni [38] investigated the performance of the structured packing cross flow air–liquid desiccant contacting surfaces on the dehumidification and regeneration of the system. A solution of $CaCl_2$ is used as a liquid desiccant. The complete experimental setup is shown in Fig. 24. The results showed that the payback period of the system is 11 months and the annual operation cost is reduced by 31.24% compared with a conventional vapor compression system (VCS). The overall environmental impact is approximately 0.63 compared to VCS.

### 3.4. Ultrasonic technology

Several researchers have studied a non-heating method using ultrasonic technology in a drying process. The result showed that it can improve drying kinetics and energy efficiency. However, some issues connected to the environment exist, including the method being an ultrasonic hazard.

Yao et al. [39] investigated five different drying models to quantify the drying kinetics of silica gel regeneration by hot air combined with ultrasonic power. The experiment setup is shown

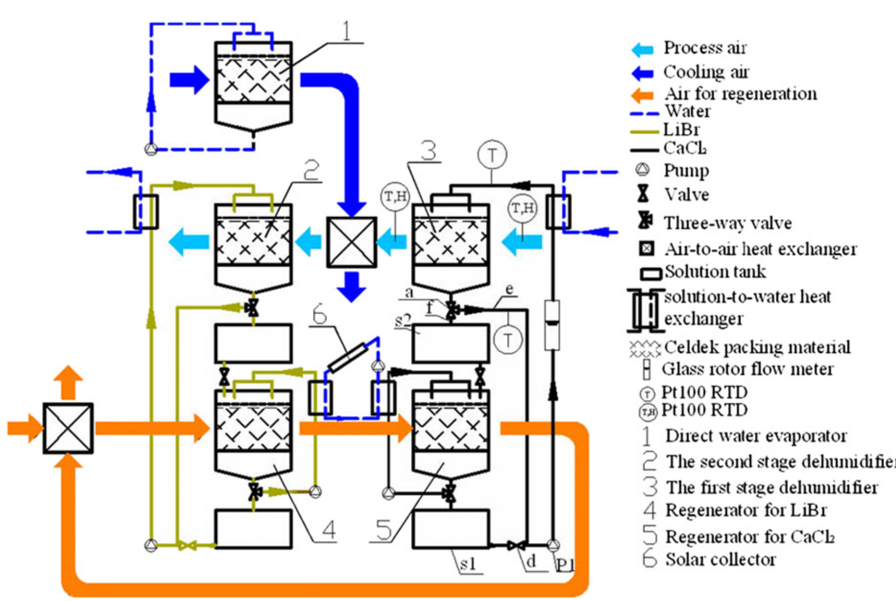


**Fig. 21.** Two stage liquid desiccant [35].

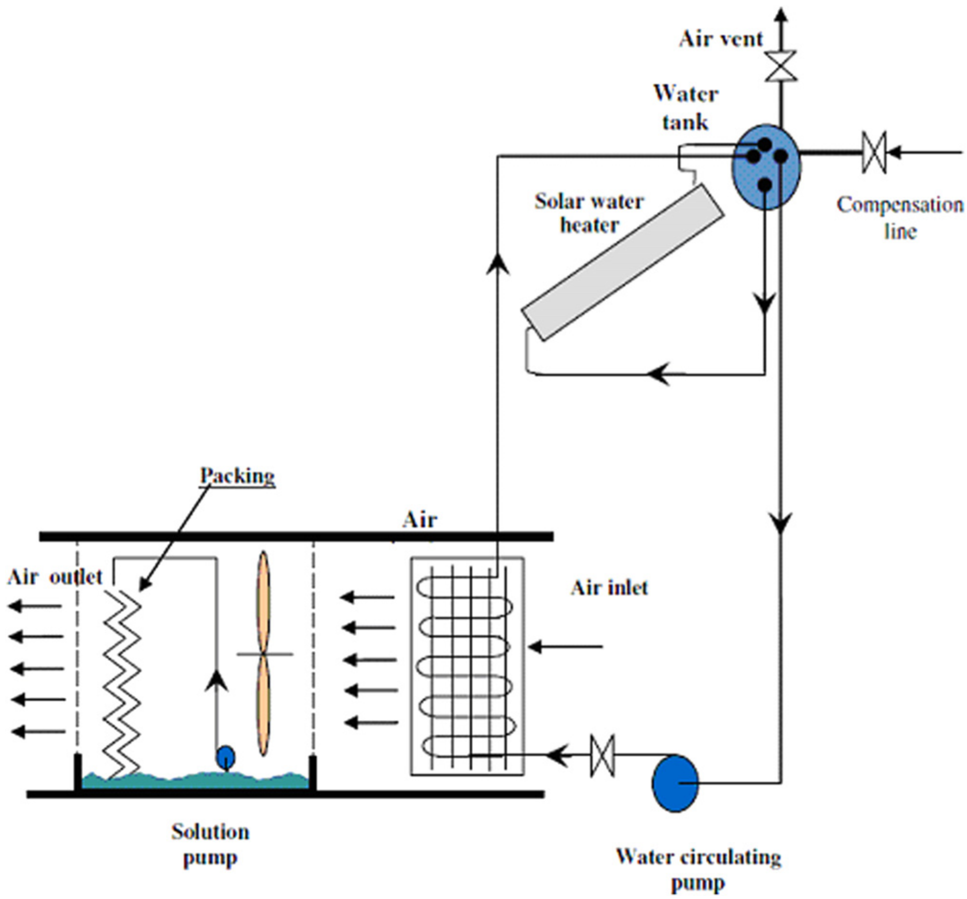


Fig. 22. Regeneration of liquid desiccant by solar energy [36].

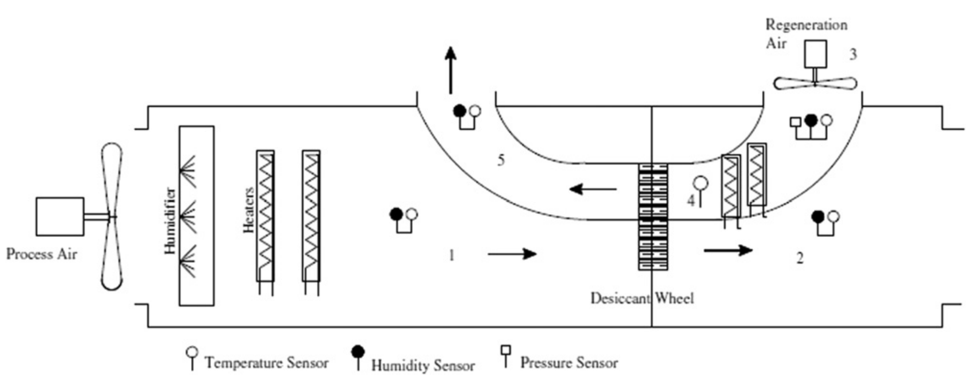


Fig. 23. Desiccant wheel experimental setup [37]. 1—Inlet process air; 2—outlet process air; 3—ambient air; 4—inlet regeneration air; 5—outlet regeneration air.

in Fig. 25. The experiments were carried out under different drying air temperatures (i.e., 45 °C, 55 °C, 65 °C, and 75 °C) with three frequencies of ultrasonic power (i.e., 21, 26, and 38 kHz) and three power levels (20, 40, and 60 W). The results indicated that acoustic power and frequency affect drying temperature and equilibrium moisture content. The regeneration of silica gel by ultrasonic power could be performed at lower acoustic frequency.

Yao [40] designed and developed an evaporative cooler using ultrasonic technology (Fig. 26). Two dehumidizer beds were integrated with ultrasonic regenerators, DU1 and DU2 (3, 4), and both took turns to operate. When the DU1 was on for regeneration of the desiccant, the DU2 was turned off, letting the desiccant attract moisture (dehumidify) from the fresh air (FA). At this time, the air valves AV1 (7) and AV4 (12) were open, while the air valves AV2 (9) and AV3 (11) were close, so FA at the upper part of the set-up passed through DU1 and removed the moisture from the desiccant assisted by ultrasonic energy. The remaining FA passed through DU2, was dehumidified, then flowed to the evaporative cooling chamber and finally entered the air conditioned space.

Yao [40] also designed the ultrasonic regenerator for the liquid-desiccant system shown in Fig. 27. The dilute solution was regenerated through evaporation. The liquid baffle was used to prevent the liquid droplets from being carried by the air stream. The dilute solution flowed along the baffle and condensed at the bottom as a concentrate solution. Regeneration with non-heating improved energy efficiency because no heat was required and the cooling process was eliminated before dehumidification.

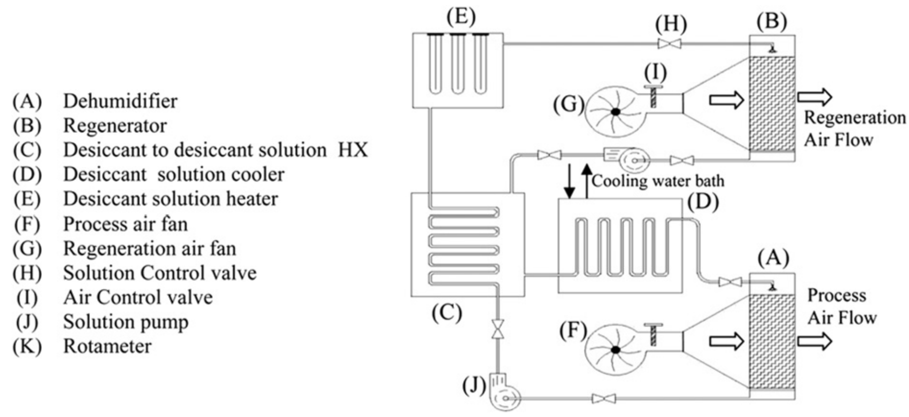


**Fig. 24.** Cross flow liquid desiccant dehumidification system [38].

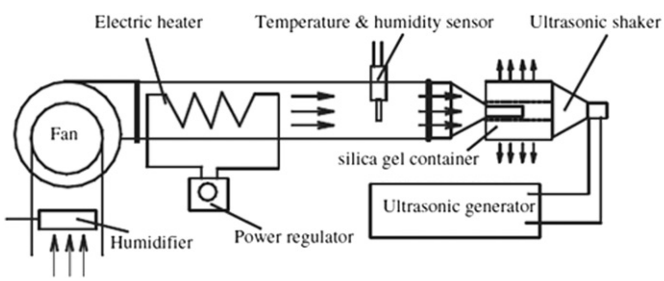


**Fig. 25.** Schematic diagram for power ultrasonic regenerator [39].

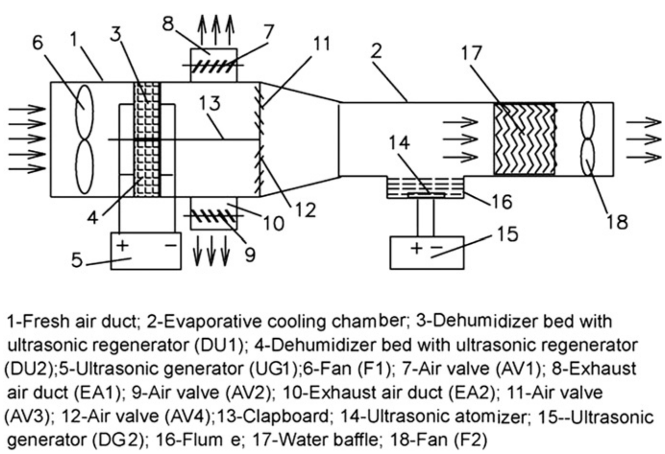


**Fig. 26.** Ultrasonic regenerator for solid desiccant [40].

### 3.5. Waste heat

The utilization of waste heat for the regeneration of desiccant material in a desiccant dehumidifier system is one of the best alternatives because regeneration cost is eliminated. However, it is only suitable for equipment which can exhaust waste heat at temperatures between 60 °C and 140 °C. Usually, these types of equipment are only available in factories or supermarkets.

The US Department of Energy (DOE) developed the Integrated Energy System (IES), which aims to improve the overall energy efficiency of distributed generation (DG) systems. The system was integrated with waste heat recovery and thermally activated (TA) technologies. Zaltash et al. [41] reported on this topic. TA systems use the DG's hot exhaust gas for heating, cooling, and regenerating the desiccant material in dehumidification systems. The main components of the system are shown in Fig. 28. The exhaust gas from the DG can be used directly or routed to a heat recovery unit

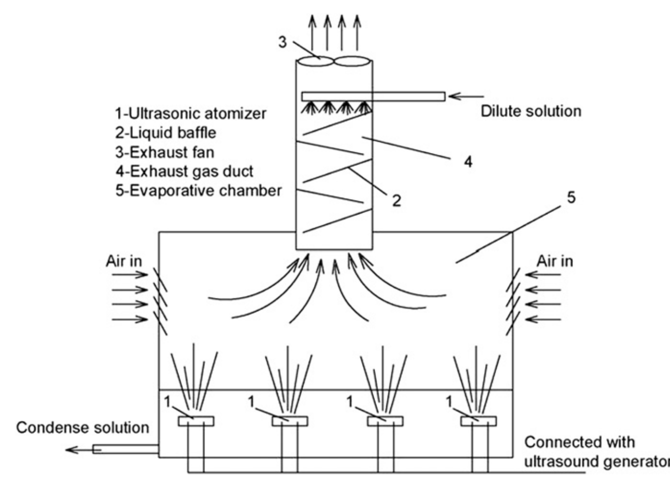


**Fig. 27.** Ultrasonic regenerator for liquid-desiccant [40].

(HRU) through an air-to-water heat exchanger. The microturbine-generator (MTG) can be operated individually or integrated with various waste heat recovery. The overall efficiency of IES increases from 5% to 7% when used with an exhaust-fired desiccant dehumidification unit (EGFDD).

De Antonellis et al. [42] investigated seven HVAC configurations for drying based on desiccant wheels to find the most energy-efficient system. The systems were designed with the integration of an adsorption wheel, refrigerating machines, and co-generative engines. The study on different ratios of ambient sensible load ($Q_s$) to ambient latent load ($Q_l$) was carried out by simulation, and the effect of outside and ambient air conditions was analyzed for each configuration. The optimal configuration depended on the $Q_s/Q_l$ value and slightly on outside and ambient conditions. The system based on a cooling coil was efficient only if $Q_s/Q_l > 0$ and was best if $Q_s/Q_l > 2$. The most common desiccant wheel configuration (Fig. 29) is recommendable when $Q_s/Q_l < -1$. It was found that primary energy consumption could be reduced from 70% to 80% compared with a conventional system based on a cooling coil.

### 3.6. Electro-osmosis

Generally, solid and liquid desiccant dehumidification techniques require heat and consume large amounts of electricity to regenerate the desiccant material, which is disadvantageous in domestic application [43]. Many studies have been carried out to find alternatives for low-cost energy in the regeneration of desiccant material.

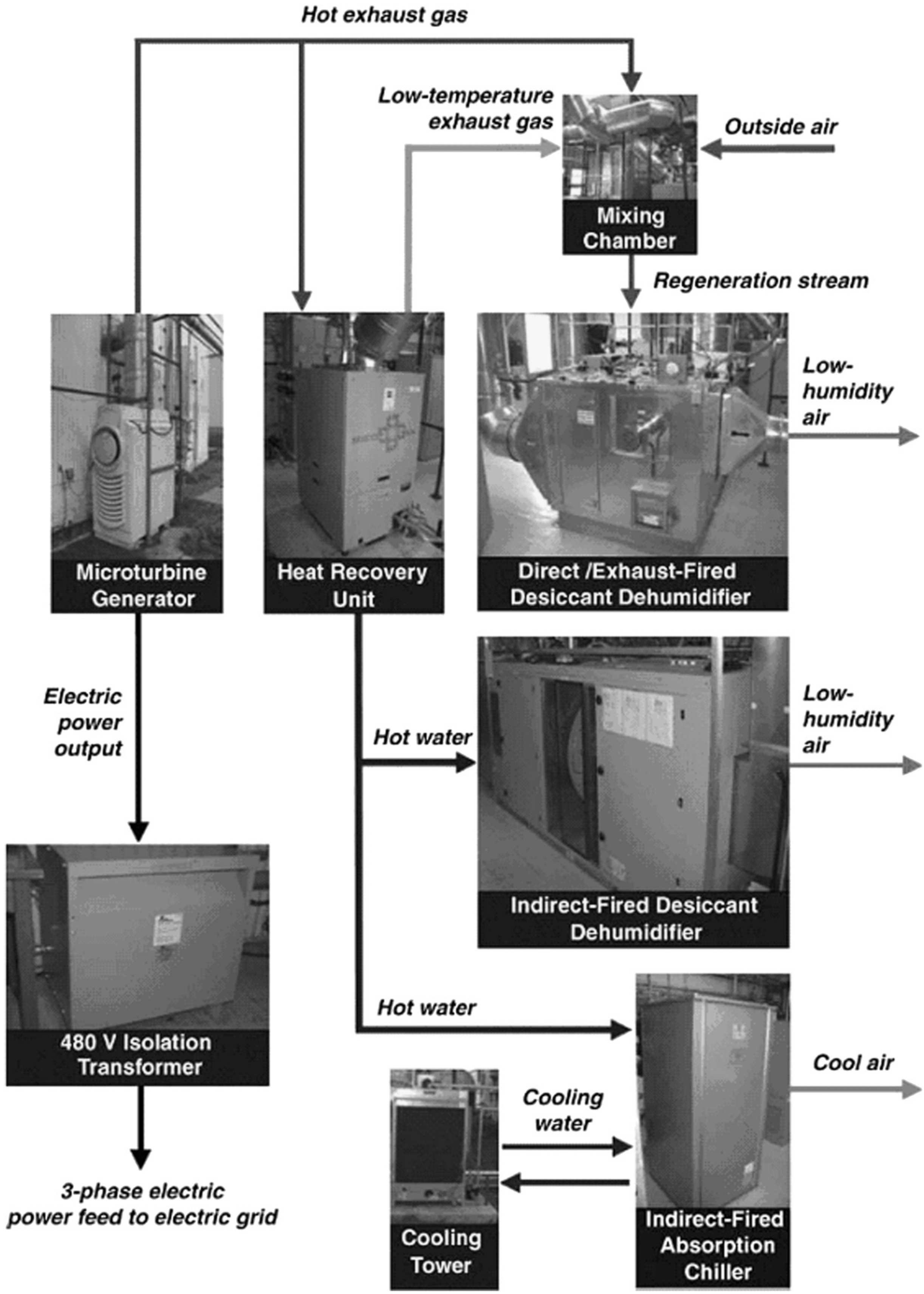


**Fig. 28.** Integrated Energy System [41].

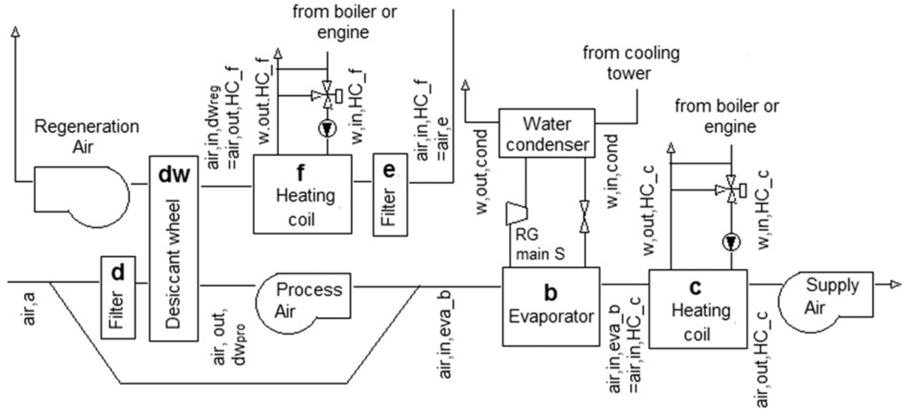


**Fig. 29.** Common desiccant wheel configuration [42].

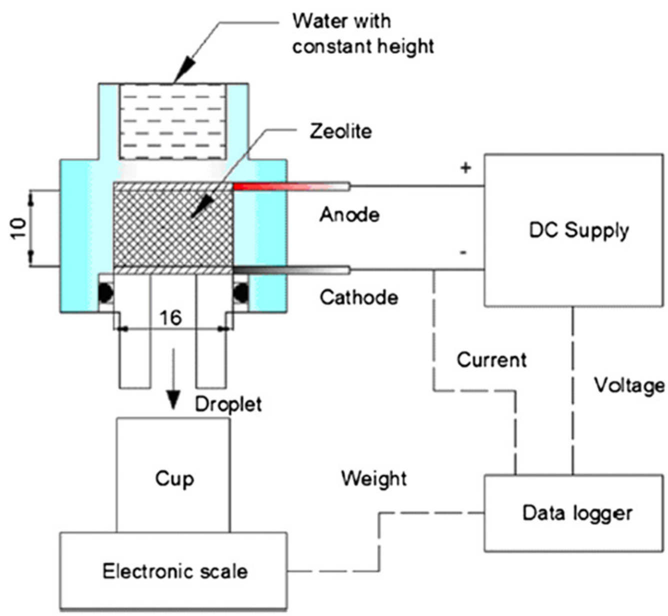


**Fig. 30.** Experimental setup of the EO regeneration system [44].

Li et al. [44] experimented on using electro-osmosis (EO) for regeneration. In this technique, low voltage DC supply is used. The use of the EO technique in air conditioning systems was found to save approximately 23.3% of energy compared to the conventional air conditioning system. The apparatus includes the EO device with zeolite as a desiccant, an electronic scale, and a data logger (Fig. 30). De-ionized water was used in the experiment. When zeolite was saturated with water by absorption, mass flow stabilized, after which 20 V DC voltages were applied. The result showed that an EO mass flow rate is achievable at 0.953 g $m^2$ $s^{-1}$.

Solar energy has high potential to be utilized as a heat source to regenerate the desiccant material. After the payback period, the drying system runs with low operating cost. However the main drawback is the intermittent of solar energy. Therefore the use of electrical heater as back-up energy is required to supply heat during off-sunshine. The regeneration of desiccant using waste heat also uses free energy source. However it can only be applied at certain locations. Integration of heat pump and desiccant system is one of the established method and cost effective to produce dry and hot air. Ultrasonic technology and electro-osmosis are considered as new methods in regeneration of desiccant material. These methods consume low energy level which is good in terms of reducing the operating cost.

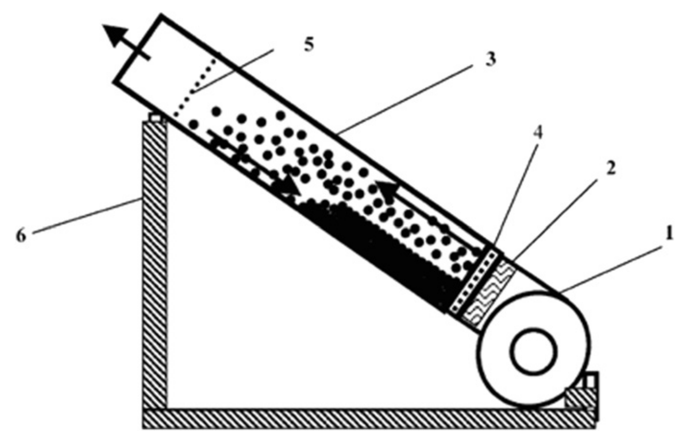


**Fig. 31.** Inclined-fluidized bed [45].

## 4. Design optimization of desiccant system

The application of a desiccant system in cooling, heating, and drying can increase its performance or efficiency, as well as reduce operating cost. However, the design of a desiccant system is very crucial to ensure it works at optimum condition. Experimental and simulation studies have been done to optimize the design of a desiccant system.

Hamed [45] investigated the adsorption and desorption operations in an inclined-fluidized bed. A circular glass tube filled with silica gel was tested at an inclination angle of 45° (Fig. 31). During adsorption, humidity and temperature were nearly constant, but flow rates were varied. The desorption time was only 15 min, whereas adsorption time was approximately 90 min until near-saturation was achieved. Adsorption and desorption rates were found to be affected highly by air stream velocity. Low regeneration temperature at 90 °C demonstrates the possibility of using solar energy for its regeneration process. Observation of the particle color in the bed shows that the distribution of moisture concentration is uniform.

Narayanan et al. [46] conducted a study on the performance of three different wheel designs. Results showed that the percentage dehumidification rate of parallel flow, normal counter flow, and counter flow with a cooling section are 16.27%, 25.05%, and 29.77%, respectively, at the selected design conditions. Without the cooling section, the dehumidification performance of counter flow is better than parallel flow.

According to the manufacturer, at high regeneration temperatures, the 1:3 area ratio of regenerative to dehumidification ($A_r/A_p$) is commonly used, whereas for low regeneration

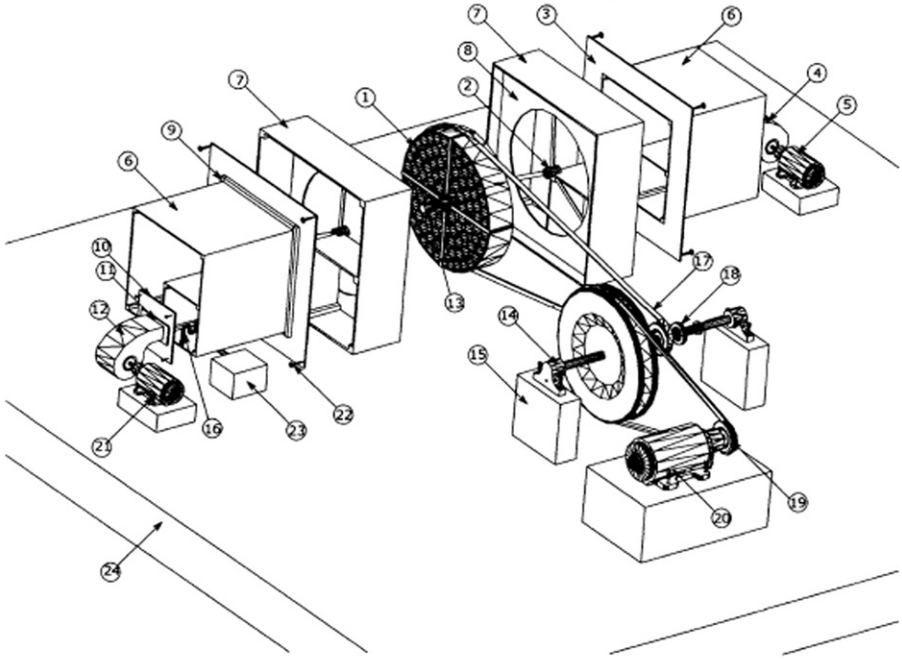


**Fig. 32.** Experimental setup of new rotating absorption disk [48].

temperatures, a 1:1 ratio is used. Chung et al. [47] conducted numerical simulation for the optimization of a desiccant wheel. The numerical simulations in the current study are in reasonable agreement with previous experimental data. Wheel speed was tested at regeneration temperatures between 60 °C and 150 °C. The optimum speed is determined when the moisture removal capacity (MRC) is at a maximum. The optimum wheel speed decreases to a nearly constant value as the regeneration temperature increases. The lower the outdoor humidity, the higher the optimum wheel speed. Moreover, at low regeneration temperatures, optimum speeds are not greatly influenced by outdoor conditions.

Hamed et al. [48] designed and constructed a new rotating absorption disk for a desiccant bed (Fig. 32). The diameter and thickness of the desiccant wheel are 50 and 10 cm, respectively. The desiccant bed consists of 350 cylindrical shape slots and is constructed from a steel spring. The spring is coated with a thick cloth layer impregnated with lithium chloride solution as the absorbing surface. Experimental data showed that the desiccant bed is capable of absorbing 95 g of water from air every hour. Based on theoretical investigation, the amount of water absorbed and desorbed is in equilibrium condition for a complete cycle at the regeneration temperature of 85 °C. At an operating temperature of 30 °C and 50% RH with lower regeneration temperature, about 13% of the processed air humidity ratio is reduced from its initial value.

A liquid desiccant can be regenerated by either hot air or hot desiccant. Liu et al. [49] investigated the heat and mass transfer performances of these two regeneration methods. The result showed that the best mass transfer methods in hot air and a hot desiccant are parallel flow and counter-flow regenerator, respectively. The heat should be used for a desiccant in a packed bed regenerator because the performance of mass transfer for a hot desiccant regenerator is higher than that for a hot air regenerator.

Zurigat et al. [50] developed an experimental setup (Fig. 33) to investigate the performance of an air dehumidifier using triethylene glycol (TEG) as a liquid desiccant. The height of the tower is 0.6 m with a structured type packing consisting of eight decks. Each deck consists of seven plates with a total packing density of 77 $m^2/m^3$ and a total height of 0.48 m. The desiccant direction was against the air stream and distributed over the packing. The moisture from humid air was absorbed by the concentrated desiccant it came in contact with. The diluted desiccant was collected into the catch tank, and then pumped to the heater tank for regeneration. The packings were made of aluminum or wood. Results showed that the moisture removal rate (MRR) increases with increasing TEG flow rate, inlet TEG concentration, and air flow rate for both types of packing materials. Meanwhile, increasing the temperature of inlet air increases the moisture removal rate for aluminum packing. Increasing the TEG inlet temperature and flow rate increases the effectiveness of the column for both packing materials.

Awad et al. [51] performed experimental and theoretical studies on the radial flow of hollow cylindrical dehumidification. Silica gel was used as a solid desiccant. Five units of hollow

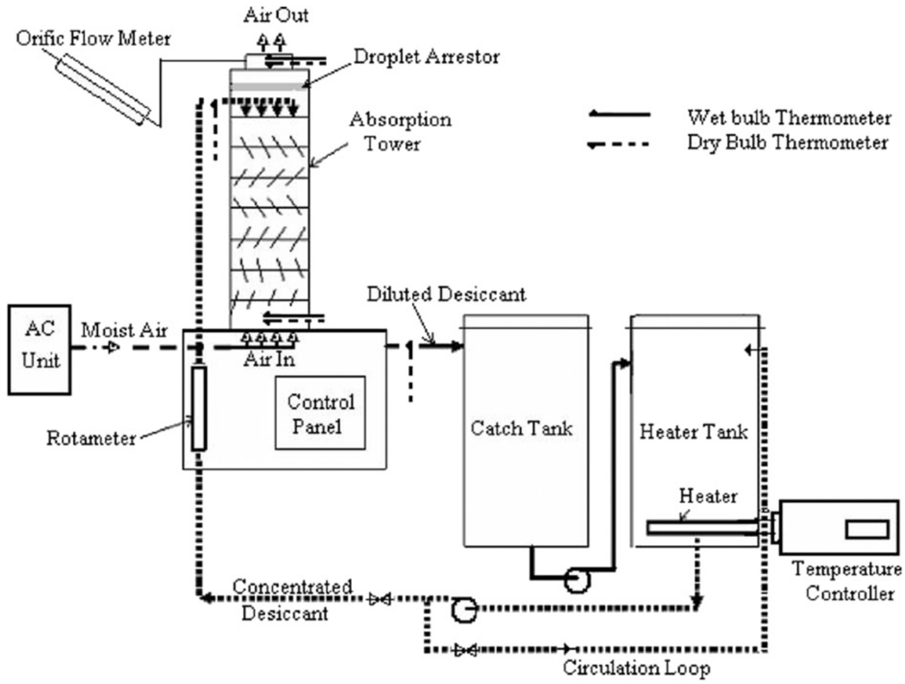


**Fig. 33.** Experimental setup for dehumidifier performance [50].

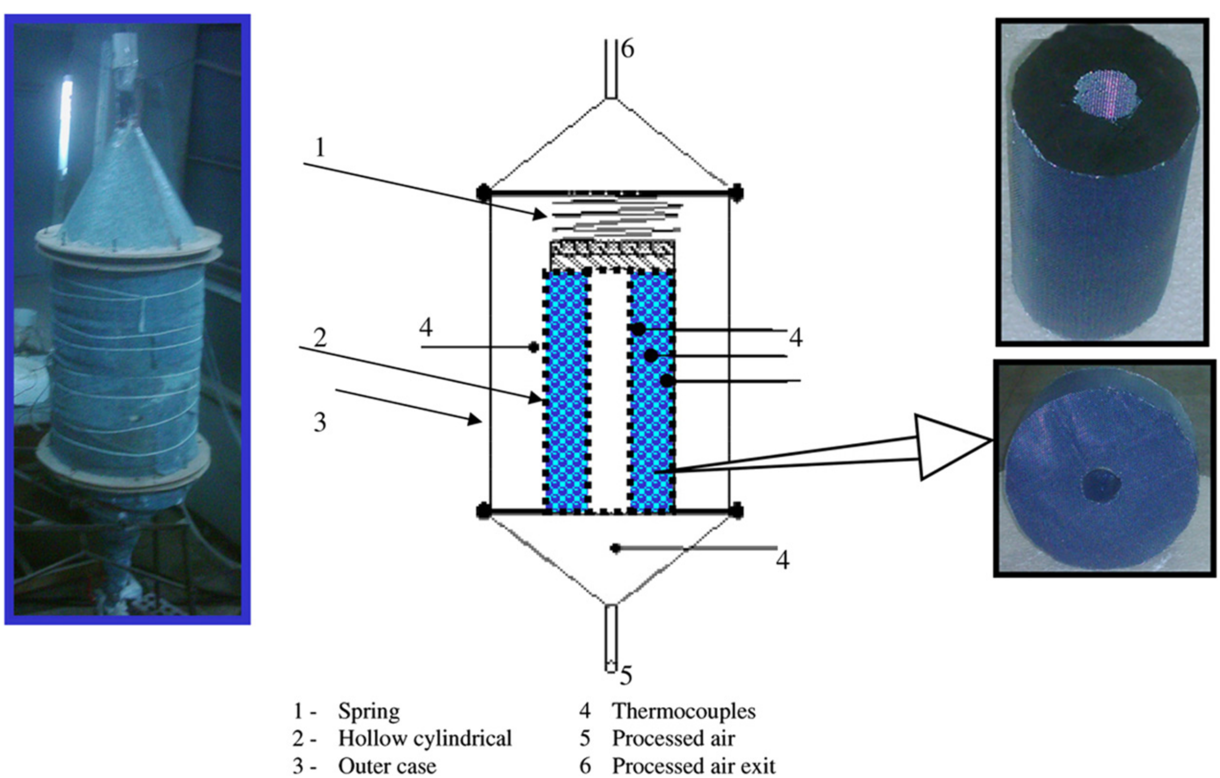


**Fig. 34.** Hollow cylindrical packed bed [51].

cylindrical beds with different ratios of diameter but nearly the same total mass were tested (Fig. 34). For the diameter ratio of 7.2, the dehumidification time was found to be limited to 15 min in order to obtain efficient operation. Increasing the bed diameter ratio increases the pressure drop of processed air. However, beds with higher bed diameter ratio values adsorb more moisture from the air.

Design optimization of desiccant system may be done by experimental or simulation studies. The optimization studies reduce the energy consumption and construction cost of the desiccant system. Meanwhile the performance of the desiccant system needs to be increased so that the system works at optimum condition. As a result, optimization will produce cost-effective and efficient desiccant system. This will enhance the potential of desiccant material in drying application from the technical and energy saving point of view.

## 5. Selection of desiccant material

Desiccants with low cost materials, low regeneration temperature, higher moisture removal rate, and stability even after several years make a desiccant system more effective in its performance and cost. However, there should be a compromise among all the criteria. For example, low cost material is usually less stable and a desiccant with a low regeneration temperature usually has lower moisture removal rate. The efforts to introduce new desiccant material or improve the existing desiccant material have been studied.

Bulut et al. [52] investigated three Turkish bentonites: (1) Ca-bentonite from Lalapaşa–Edirne region (LLP), (2) Na/Ca-bentonite from Çankırı region (CNK), and (3) Na-bentonite from Reşadiye–Tokat region (RSD). These bentonites consist of smectite and small amounts of quartz, feldspar, calcite, and opal-CT, as well as some amounts of zeolite and dolomite. The raw samples were estimated at 75–80%, 50–55%, and 75–80% for LLP, CNK, and RSD, respectively. LLP has the highest moisture adsorption at 17.1% after heating at 150–200 °C, CNK 8.3% at 105 °C, and RSD 6.4% at 105 °C. The addition of $CaCl_2$ is necessary to increase the moisture adsorption capacity.

Tretiak and Ben Abdallah [53] developed a type of desiccant consisting of clay and $CaCl_2$ for multiple sorption and desorption cycles testing. The desiccant was made with a weight ratio of commercial kaolin clay to vermiculite, 3:0.44. The desiccant consisted of 18.5% (db) $CaCl_2$. The experimental setup is shown in Fig. 35. The inlet air conditions during sorption test for temperature, relative humidity, and velocity were in the range of 23–36 °C, 42–66%, and 0.17–0.85 m/s, respectively. The inlet air temperature and velocity during desorption test were 50–57 °C and 0.30–0.60 m/s, respectively. The sorption/desorption experiments were repeated, causing the surface of the desiccant material to break down, although the overall structure of the desiccant was maintained.

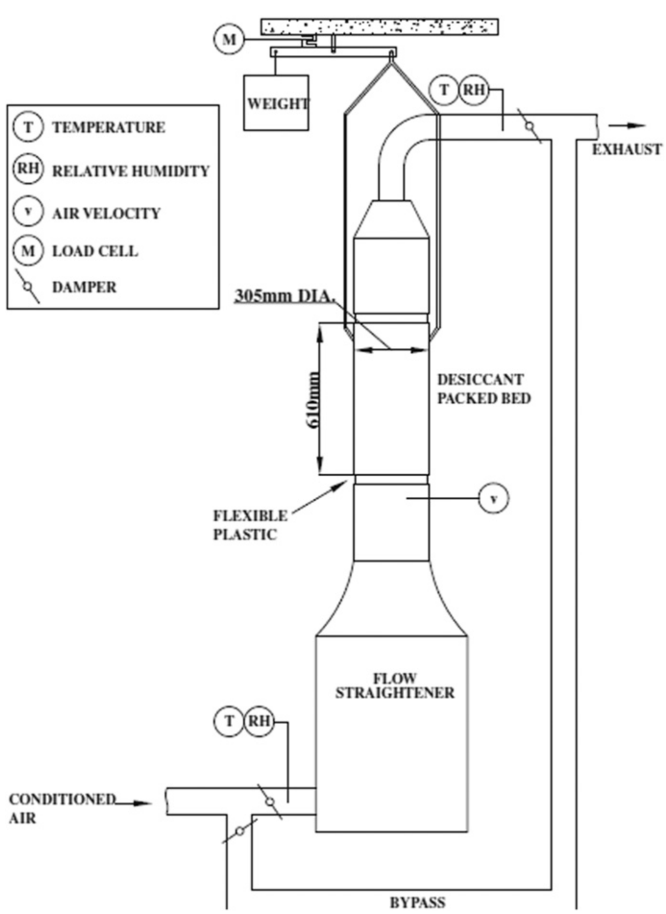


**Fig. 35.** Desiccant test setup [53].

Nakabayashi et al. [54] developed a low regeneration of desiccant material. A natural mesoporous material from Japan known as Wakkanai siliceous shale (WSS) was impregnated with $CaCl_2$, lithium chloride, or sodium chloride to improve the ability of WSS to adsorb/desorb the water vapor. Its mesoporous structure is similar to B-type silica gel. The water vapor adsorption increases from five to seven times when natural shale is impregnated with sodium chloride at relative humidity between 50% and 70%. The effective impregnating concentration were determined as 5 wt% based on the relationship between the maximum amount of water vapor adsorption and the mesopore volume. The experimental setup is depicted in Fig. 36. The air conditions for regeneration and adsorption process are 40 °C with relative humidity of 27%, and 30 °C with relative humidity of 75%, respectively. The new filter is capable of adsorbing and desorbing 60 g/h water vapor at the regeneration temperature of 40 °C. Meanwhile, a zeolite filter and a silica gel filter adsorbs and desorbs only 25 g/h and 10 g/h, respectively.

Zhang et al. [55] studied and compared the abilities of three composite materials used in a desiccant rotary wheel to remove moisture from humid air (Fig. 37). The materials used were silica gel (SG), $CaCl_2$, and a composite desiccant (SG–$CaCl_2$) applied to a desiccant wheel of corrugated paper (CP). The result showed that the CP–SG–$CaCl_2$ composite reaches equilibrium faster than other samples. The CP–SG–$CaCl_2$ wheel also has a longer lifespan than the CP–$CaCl_2$ wheel due to the solidification effect of SG.

Ramzy et al. [56] studied the effect of using composite particles as desiccant material in a packed bed dehumidifier. An inert particle was used to replace the unutilized area of the spherical desiccant particle. The proposed silica gel composite particle increased the area for heat and mass transfer. A modified solid side resistance (MSSR) model was developed and showed agreement with the experimental results. Particles with thickness ratio of 0.2 decreased the pressure drop by about 60%, whereas total mass adsorbed and desorbed increased by about 11.07% and 20.46%, respectively, compared with conventional silica gel. The bed effectiveness increased by 15.5%. The thermo-physical properties of the inert material affected the total mass adsorbed/desorbed for thickness ratio by less than 0.5.

Dawoud and Aristov [57] conducted an experiment on the kinetics of water vapor sorption on composite materials (SWS-1L and SWS-1A) and host materials (mesoporous silica gel and alumina). Both composites are formed by impregnating the host matrices with $CaCl_2$. The experiment was done on 3 g samples on an isothermal wall under three different operating conditions of a sorption heat pump (SHP). The experimental setup is depicted in Fig. 38. SWS composites were found to take four times as long to reach 50% of the final differential water loading compared with the host materials. However, SWS composites take approximately 4–5 min, which is appropriate for applying SWS to SHP applications. SWS-1L has faster kinetic water sorption than SWS-1A, which only needs about 60% to 80% of the time required for SWS-1A to reach 50% of the final differential water loading.

Longo and Gasparella [58] developed a packed column dehumidifier/regenerator with a liquid desiccant. The experimental setup is shown in Fig. 39. The traditional hygroscopic salt solutions $H_2O$/LiCl and $H_2O$/LiBr, and the new salt solution $H_2O$/KCOOH were tested under the typical operation of air conditioning. The hygroscopic salt solutions were found to be capable of reducing air humidity constantly. The regeneration of the

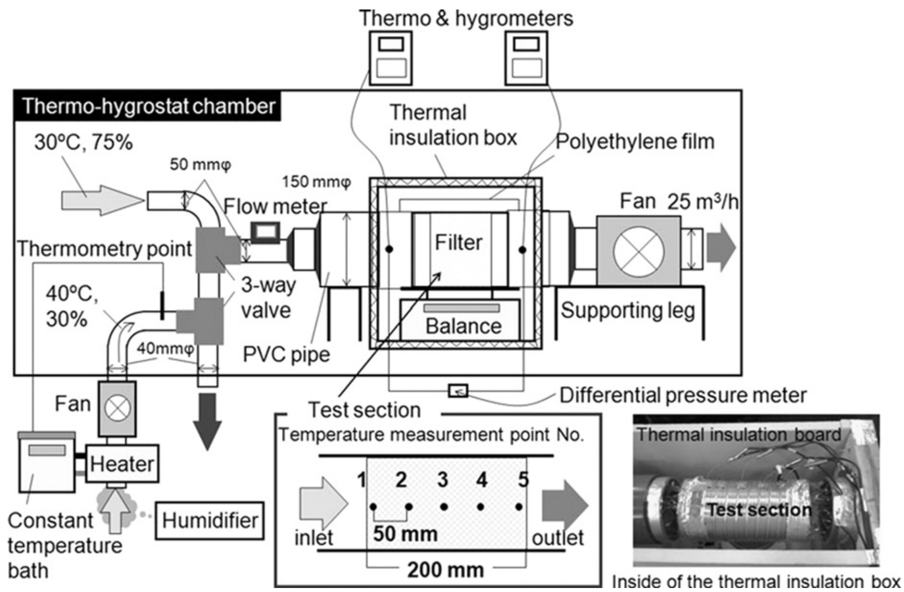


**Fig. 36.** Adsorption/regeneration test of WSS [54].

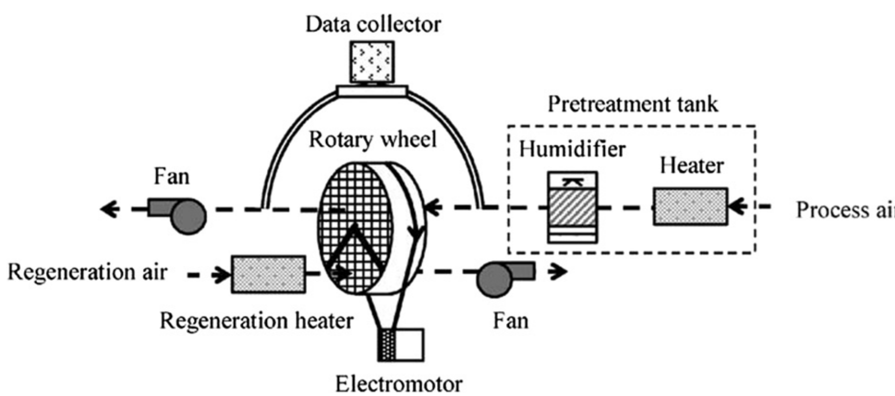


**Fig. 37.** Experimental set-up of adsorption test [55].

desiccant can be performed at temperature between 40 °C and 50 °C. Although the dehumidification performance of $H_2O$/LiCl and $H_2O$/LiBr is better than that of $H_2O$/KCOOH, it is not the case in regeneration performance. The new solution $H_2O$/KCOOH is less corrosive, though its price is higher than a traditional desiccant. The experiment on hygroscopic solution $H_2O$/LiBr was also carried out to test desiccant regeneration in two different packed columns: a random column consisting of 1 in. Pall Ring elements and a structured column Mellapack 250Y [59]. Regeneration performance of the random column was 20–25% higher than the structured column because the former has a larger contact area per unit volume. However, the air side pressure drop for the structured column was about 65–75% lower.

Al-Farayedhi et al. [60] carried out a theoretical study on heat and mass coefficients in an air-desiccant contact system using a liquid desiccant. A gauze-type structured air dehumidifier was selected because it has good heat and mass transfer characteristics. The evaluated liquid desiccants were $CaCl_2$, lithium chloride, and a mixture of both solutions with a mass ratio of 1:1. Results showed that the mass transfer coefficient of the mixture solution is higher compared to a $CaCl_2$ solution.

Cinar et al. [61] investigated the capability of three different sepiolite samples from the Eskişehir region of Turkey. The percentage of adsorbed humidity increased to 20% and 30% at 50% RH and 90% RH, respectively. For heat treatment tests, sepiolites were placed in a thermostatically controlled oven with temperature range between 90 °C and 500 °C as a function of time. The tests, with the addition of $CaCl_2$, were done against RH, temperature, and treatment time. Raw sepiolites at 50% RH were not unable to fulfill desiccant standards. Therefore, $CaCl_2$ was mixed with sepiolites at different percentages to evaluate its capability to adsorb humidity. Finally, the sepiolite mixed with 5% $CaCl_2$ at 50% RH or above presented better adsorption capabilities than a commercial desiccant.

Jain et al. [62] developed an experimental setup (Fig. 40) to study the performance of a liquid desiccant dehumidification system. $CaCl_2$ and lithium chloride were used as liquid desiccants. The cooling tower was constructed in the system with packed beds of cellulose structures for evaporative cooling. The design of the contactor is shown in Fig. 41. In the setup, heat transfer occurs when outside air (OA) and liquid desiccant are in direct contact with the contactor. The moisture from OA is absorbed by the liquid desiccant to produce dried supply air. Water content from the hot desiccant is transferred to FA in the regenerator, and then hot and wet air pass through the air-to-air heat exchanger (A/A HX) before being released to the ambient. The FA that enters the regenerator passes through the A/A HX for preheating and then moves to the desorber. The electrical heater is used to heat the liquid desiccant in a solar collector temperature. The system was found capable of producing lower change in specific humidity for

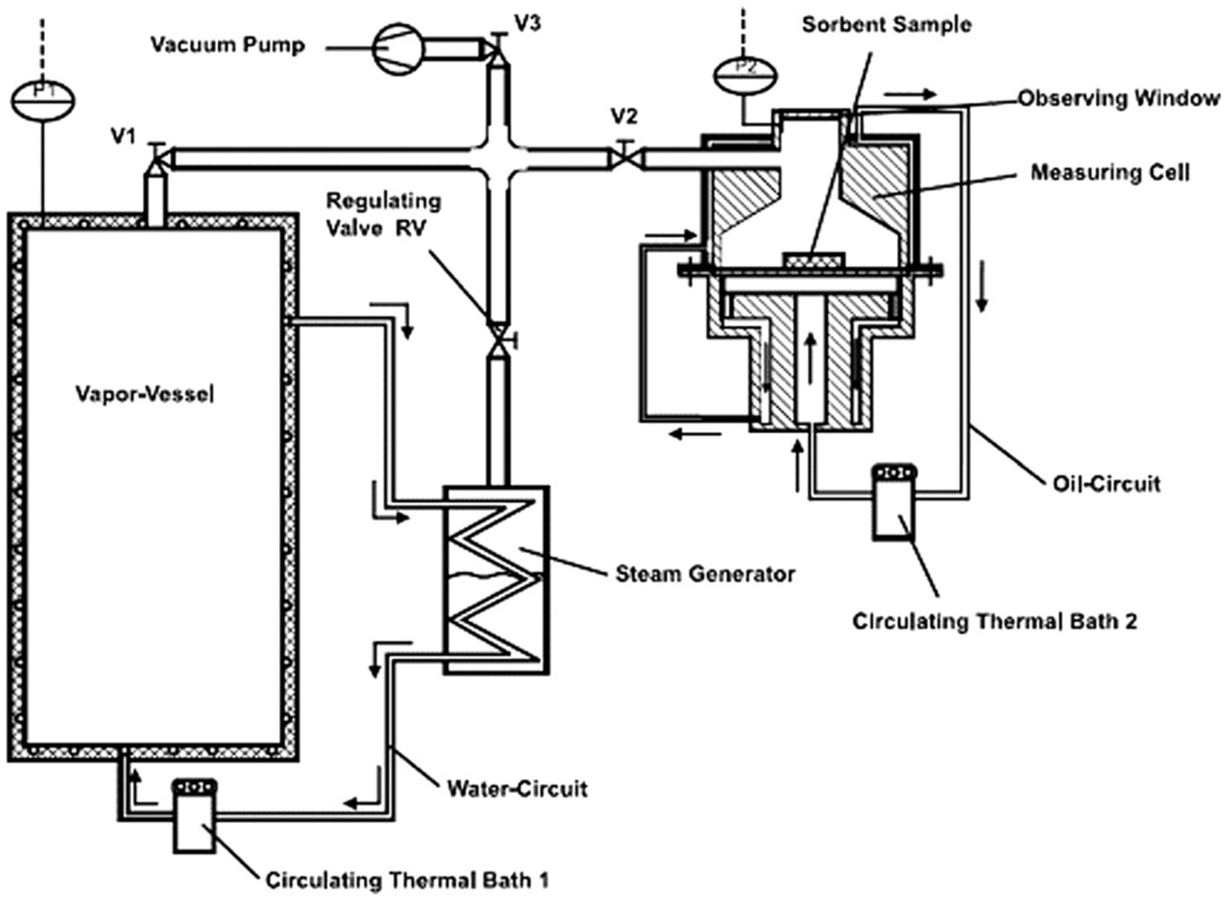


**Fig. 38.** Test-rig for measuring the kinetics of water vapor sorption [57].

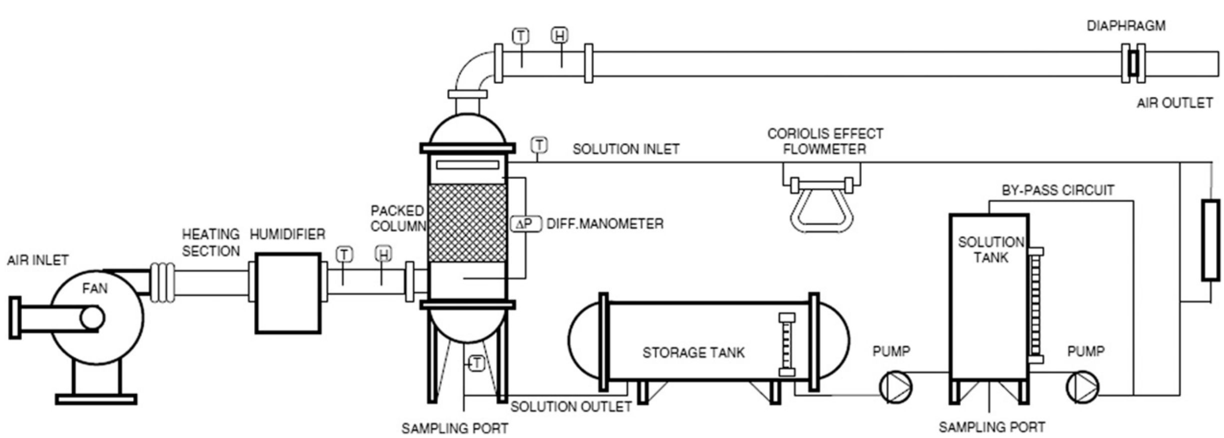


**Fig. 39.** Experimental setup of packed column dehumidifier/regenerator for liquid desiccant [58].

$CaCl_2$ in the range of 0.6–1.77 g/kg, with dehumidifier effectiveness and regenerator effectiveness in the range of 0.25–0.44 and 0.07–0.80, respectively. The change of specific humidity using lithium chloride is better than $CaCl_2$ in the range of 3.67–5.86 g/kg, with dehumidifier effectiveness between 0.36 and 0.45.

The use of natural material as a desiccant is environmental friendly and the material can be obtained easily. The knowledge on character and properties of the desiccant materials is necessary to find the effective desiccant to adsorb humidity. The established liquid desiccants are calcium chloride and lithium chloride, while solid desiccant are silica gel, alumina silicate, and zeolite. However composite desiccant materials may improve the moisture adsorption capacity of the material. The moisture adsorption capacity depends on heat and mass transfer characteristics.

## 6. Conclusion

The reviews on solid/liquid desiccant in drying application and its regeneration methods were carried out. From the reviews the following conclusions can be drawn:

1. Desiccant system in drying application has several advantages including continuous drying even during off-sunshine hours, increased drying rate due to hot and dry air, more uniform

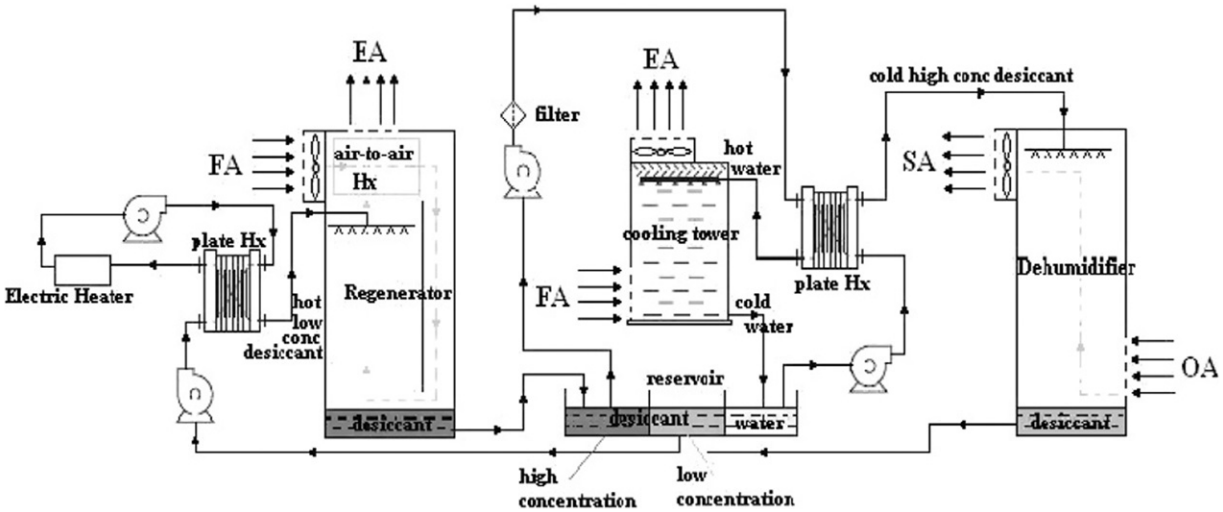


**Fig. 40.** Experimental setup for dehumidification system [62].

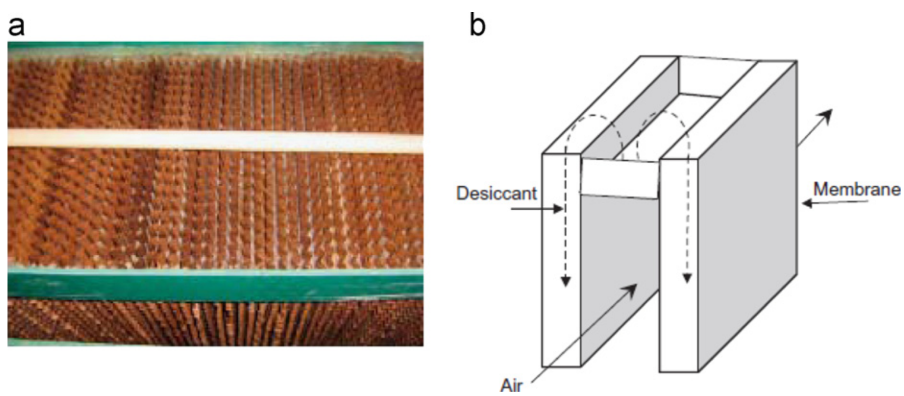


**Fig. 41.** Design of contactor [62]. (a) An inside view of the contactor in dehumidifier, (b) flow of desiccant and air inside the contactor.

drying, and increased product quality especially for heat-sensitive products.

2. Some problems in desiccant system such as pressure drop in solid desiccant and carry over of liquid desiccant by air stream may be eliminated or reduced by optimization of the design of desiccant system. The design optimization of desiccant system will enhance the potential from the technical and energy saving point of view.
3. The use of heat to regenerate desiccant material in a drying system has limitations in energy saving. Therefore, the desiccant material with low regeneration temperature is preferable.
4. The use of solar energy or waste heat from industrial processes for regeneration of desiccant material will make the system run at low operating cost.
5. The use of composite desiccant materials may improve the moisture adsorption capacity of the material.

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