1

Introduction

1.1 Background

Dehumidification is an important air-handling process in the air-conditioning system, which aims at reducing the level of humidity in the air. This is usually for health reasons, as humid air can easily result in mildew growing inside a residence and causing various health risks [1]. It is also necessary in many industrial or agricultural situations where a certain low level of air humidity ought to be required to be maintained. Traditionally, the moist air is commonly dehumidified through the refrigerant cooling method, that is, the air is first cooled below the dew-point temperature (DPT) to condense moisture out, and then reheated to a desired temperature before it is delivered to the occupied spaces. This method not only results in additional energy dissipation due to the cooling–heating process, but also works against the energy performance of the chiller system because of the lower refrigerant evaporating temperature required. To improve the energy efficiency of the air-conditioning system, an independent humidity control system that integrates liquid/solid desiccant devices with a conventional cooling system has been developed to separate the treatment of sensible and latent load of moist air [2–4]. This system can bring about high chances of energy conservation, for example, avoiding excess cooling and heating, utilizing waste heat rejected by machines [5], and solar energy [6] to accomplish the dehumidification. Furthermore, dehumidification with dehumidizers has been proved to be beneficial for improving IAQ (Indoor Air Quality) [7].

As shown in Figure 1.1, the working cycle of the desiccant dehumidification method consists of the following three stages: adsorption (from *A* to *B*), regeneration or dehydration (from *B* to *C*), and cooling (from *C* to *A*). During the repeated adsorption–regeneration–cooling cycle, the regeneration conditions will produce great influence on the performance of water vapor adsorption on dehumidizer [8]. Although the higher regeneration temperature will contribute to increasing the desiccant volume of dehumidizer, it may be disadvantageous to the energy efficiency of the desiccant system because high-temperature regeneration will not only consume a large amount of thermal energy for heating, but also result in much energy dissipation during the following process of cooling. In addition, a higher regeneration temperature is not beneficial for utilizing the low-grade thermal energy which can be freely available. From this point of view, new types of dehumidizers [9] with lower regeneration temperatures are attractive in this field of application. In fact, the limitation of high regeneration temperature for the traditional

Ultrasonic Technology for Desiccant Regeneration, First Edition. Ye Yao and Shiqing Liu.

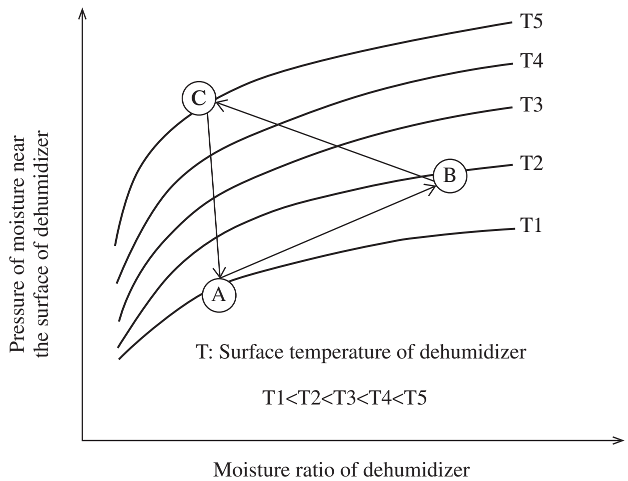


Figure 1.1 Working cycle of dehumidification using dehumidizer

desiccants may be overcome by some nonheating dehydration methods, such as centrifugal forces [10], pulsed vacuum [11], pulsed corona plasma [12, 13], and electro-osmotic [14, 15]. These nonheating methods help enhance heat and mass transfer in media through some kind of physical force, and this makes it possible to reduce the regeneration temperature of desiccants.

The high-intensity ultrasound is another nonheating technology that can improve the dehydration process of moist material, and hence becomes a promising regeneration method for desiccants [16]. Some researchers [17–21] have studied the regeneration of some adsorbents with ultrasound, such as the activated carbon and resins of different sorts. They found that the special effects (e.g., cavitation and micro-oscillation) induced by high-intensity ultrasound could overcome the affinity of the adsorbed species with the adsorbent surface and accelerate the molecular transport toward and from the adsorbent surface, and hence, the regeneration rate of these adsorbents would be greatly improved under the impact of ultrasonic radiation. The regeneration of the adsorbents for water treatment is made in the solid–liquid system where the mass transfer occurs on the interface between solid and liquid, while the desiccant regeneration is often performed in either solid–gas or liquid–gas environment.

In recent years, we have made a series of studies on the new regeneration method with ultrasound [22–58], based on which this book is edited. The primary objectives of this book are to illustrate clearly the impact of ultrasound on the regeneration of solid and liquid desiccants used in the air-conditioning systems, and manage to reveal the mechanism of regeneration enhancement brought by ultrasound. Meanwhile, the design theories of the ultrasonic transducers for the desiccant regeneration are discussed, and the desiccant air-conditioning systems based on ultrasound-assisted regeneration are proposed.

1.2 Literature Reviews

1.2.1 Desiccant Materials

Desiccants are a class of adsorbents/absorbents that have a high affinity for water vapor. They can be either liquids or solids. Examples of liquid desiccants are salt solutions, such as lithium chloride or calcium chloride, and some organic liquids, such as triethylene glycol. Since the 1930s, liquid desiccants have been used in industrial dehumidifiers. The liquid desiccants used in these systems commonly are very strong solutions of ionic salts of lithium chloride and calcium chloride. These ionic salts have the attractive characteristic that the salt themselves have essentially zero vapor pressure, and so vapors of the desiccant will not appear in the air supplied by the liquid desiccant air-conditioning system (LDACS). However, the liquid desiccants (chemically related salt solution, for example, solutions of lithium and calcium chloride) are normally corrosive. This corrosiveness requires that all wetted parts within the LDACS be protected and that no droplets of desiccant are entrained in the supplied air.

Solid desiccants are highly porous materials that adsorb water by mechanisms of chemical adsorption of water molecules onto sites on the walls of the pores, physical adsorption of successive layers of water molecules, and capillary condensation within the pores. Examples of solid desiccants are silica gel, molecular sieves, and natural zeolites. Silica gel, which is made of highly porous amorphous silicon oxide binding water molecules in random intersection channels of various diameters, has been widely used for the air dehumidification and cooling system [59–63] due to its relatively lower regeneration temperature compared with other desiccants like molecular sieves. The silica gel's adsorption capacity is relatively small at low humidity levels but increases as humidity rises. Figure 1.2 compares linear isotherm with typical isotherms for molecular sieve and silica gel [64]. It shows that the silica gel has a larger moisture adsorption capacity than the molecular sieve when the air humidity is above 40%. At room temperature in saturated air, silica gel will pick up 35–40% of its weight in moisture.

To develop the new desiccant materials with improved sorption capacity and low regeneration temperature for the air-conditioning applications, the hybrid desiccant materials impregnating a host porous material (silica gel, vermiculite) with hygroscopic salt (calcium

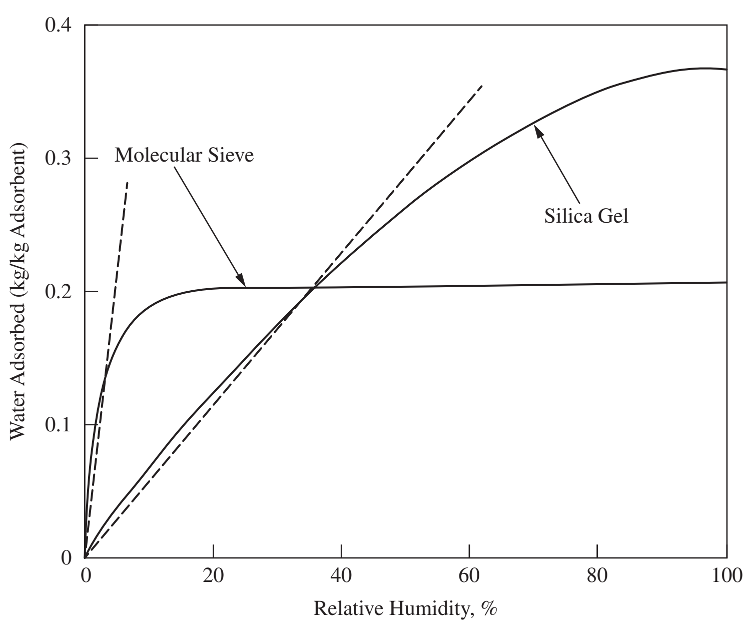


Figure 1.2 Linear approximation to properties of silica gel and molecular sieve

chloride, lithium chloride) have been put forward and studied by Aristov *et al*. [65–69]. Thoruwa *et al*. [70] developed low-cost solar regenerative solid clay–$CaCl_2$-based desiccants to continue the drying process at night. The compositions of the desiccants were given by percentage of mass. The bentonite–$CaCl_2$ (type 1: 60% bentonite, 10% $CaCl_2$, 20% vermiculite, and 10% cement) desiccant had a maximum moisture sorption of 45% (dwb (dry weight basis)). The moisture sorption of Bentonite $CaCl_2$ (type 2: 65% bentonite, 5% $CaCl_2$, 20% vermiculite, and 10% cement) and kaolinite–$CaCl_2$ (type 3: 65% kaolinite, 5% $CaCl_2$, 20% vermiculite, and 10% cement) desiccants were the same with values of 30% (dwb). Liu and Wang [71] obtained a composite adsorbent used for air dehumidification by impregnating silica gel with calcium chloride. And Jia *et al*. [72], developed a new composite desiccant material for the high-performance cooling system. The composite desiccant was a two-layered material that consists of a host matrix with open pores (silica gel) and a hygroscopic substance (lithium chloride) impregnated into its pores. The pore surface area of the composite desiccant was 194 m^2/g and the pore diameter was 3.98 nm.

1.2.2 Types of Desiccant Dryer

Each type of desiccant materials 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 applications.

1.2.2.1 Solid Desiccant Drying System

Solid desiccants cause a pressure drop in the processed air when it passes through the desiccant material. Solid desiccant systems are normally in the form of stationary or rotary wheel beds for packing the desiccant materials [73].

A system with a pre-cooler, double-stage systems (two desiccant wheels and a four-partition desiccant wheel type), and a batch system with an internal heat exchanger is presented in Figure 1.3. The batch system with the internal heat exchanger was found capable of operating at the lowest heated air temperature around 33 °C and at a cooled air temperature of 18 °C [74].

A solar dryer system integrated with desiccant material to dry fresh maize was constructed by Thoruwa *et al*. [75]. As shown in Figure 1.4, a flat plate solar air heater is connected to the drying chamber and the solid desiccant material is mounted above the maize bed. Bentonite clay and $CaCl_2$ materials are selected as desiccant materials due to their low cost and high moisture sorption. The desiccant has a moisture sorption of 45% and can be regenerated at 45 °C. The saturated desiccant bed is regenerated by solar energy during daytime. The dryer can dry 90 kg of fresh maize from 38 to 15% within 24 h.

Thoruwa *et al*. [76] built and tested a prototype dryer that provides dehumidified air at night using solid bentonite $CaCl_2$ as the desiccant material (as shown in Figure 1.5). A photovoltaic panel and a 12 V battery were used to drive the electric fan and produce constant air flow. The collector had an area of 0.921 m^2 containing 32.5 kg of desiccant, which could produce an airflow of 2 m^3/min throughout the night. The relative humidity of the dehumidified air was about 40% below the ambient level and the temperature increased by 4 °C. The desiccant was regenerated by solar radiation during the daytime. The system could capture and utilize more than 50% of the incident solar energy.

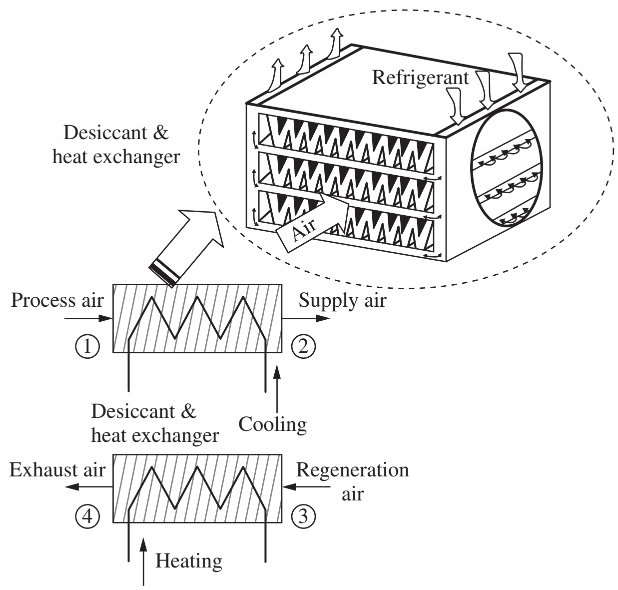


Figure 1.3 Batch-type system with internal heat exchanger [74]

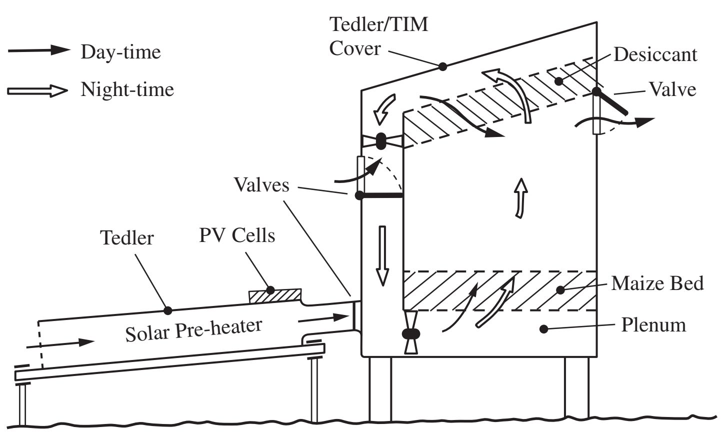


Figure 1.4 Operation of solar-desiccant dryer [75]

Shanmugam and Natarajan [77] developed forced convection and desiccant integrated solar dryer (as shown in Figure 1.6) to investigate its performance. Bentonite–$CaCl_2$ (type 1) was used as the desiccant to continue the drying operation during the off-sunshine hours, during which air inside the drying chamber was circulated through the desiccant bed by a two-way fan. During the 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 the desiccant drying system produced more uniform drying and improved

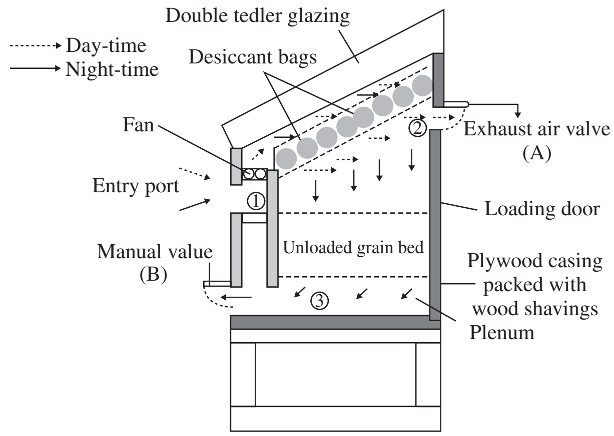


Figure 1.5 Integrated desiccant/collector dehumidifier [76]

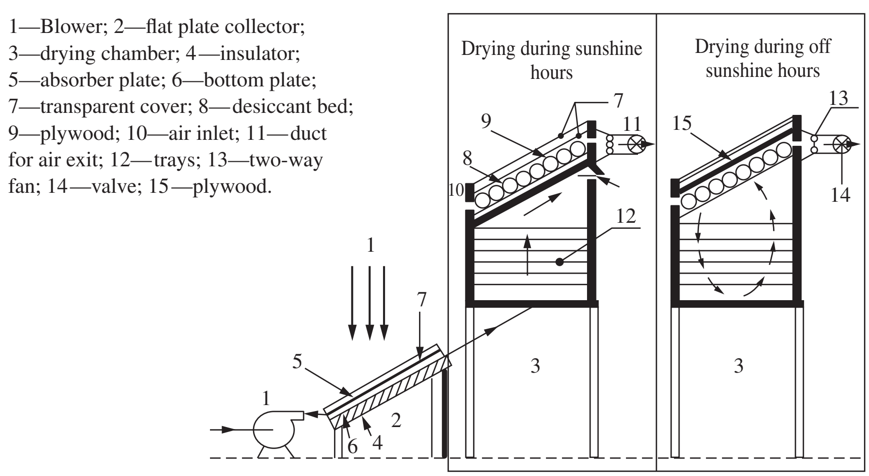
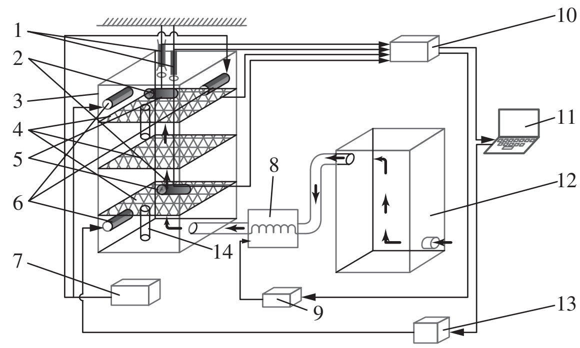


Figure 1.6 Desiccant integrated solar dryer [77]

the quality of the dried product. The characteristic and structural integrity of the desiccant remained stable even after a year. A reflective mirror was used to concentrate solar radiation on the desiccant bed. The reflective mirror improved drying performance of the desiccant by 20% and decreased drying time by 4 and 2 hours for pineapple and green peas, respectively.

Nagaya *et al*. [78] designed and developed a desiccant-based low temperature drying system to dry vegetables (as shown in Figure 1.7). The drying system was equipped with heating and air circulation control to maintain a constant temperature of 49 °C. Experimental results showed that drying vegetables using this technique produced good product uniformity and maintained their fresh color, original texture and shape, and high vitamin content. The desiccant-rotor dehumidifier was divided into three zones: an operating zone in which the



1—Linear potentiometer; 2—Net for sample; 3—Drying chamber; 4—Rack with netting; 5—Thermal transducer; 6—Fan; 7—DC power supply; 8—Heater; 9—Control box; 10—DSP; 11—Computer; 12—Dehumidifier; 13—Amplifier; 14—Thermometer

Figure 1.7 Desiccant drying system with controlled temperature and airflow [78]

silica gel captured moisture from the air (supplying dry air to the drying chamber), a recovery zone in which wet air was heated and blown out and a heat collection zone in which the silica gel released heat to external fresh air.

Madhiyanon *et al*. [79] developed a hot-air drying system integrated with a rotary desiccant wheel (as shown in Figure 1.8) to dry coarsely chopped coconut pieces. The dryer consisted of two air circuits. The first air circuit dried the product and operated in a closed or partially open system. The second air circuit regenerated the desiccant. Ambient air was dehumidified through the adsorption section of the desiccant wheel, while heated air from the second air circuit regenerated the saturated desiccant to remove moisture. A blower was 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.

1.2.2.2 Liquid Desiccant Drying System

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 [80].

Rane *et al*. [81] 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 120–185% higher. The generation process is divided into two stages (as shown in Figure 1.9). 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.

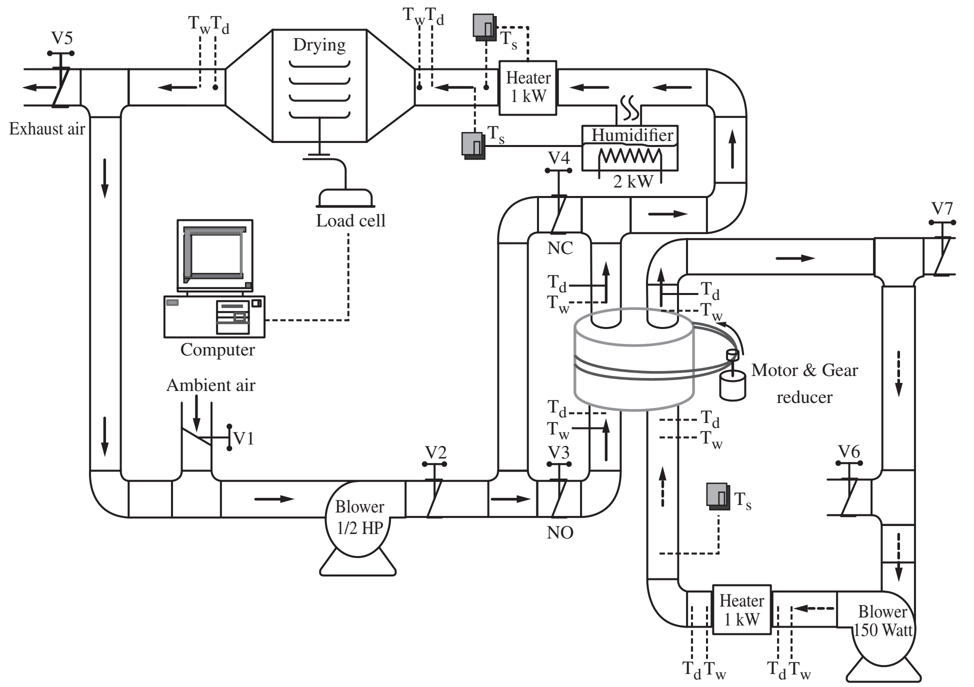


Figure 1.8 Hot-air dryer integrated with rotary desiccant wheel [79]

The liquid desiccant drying method has been used in drying green gel cast ceramic parts to shorten the drying time and to avoid defects due to the release of residual stresses. Barati *et al*. [82] studied the kinetics of one-dimensional drying of green gel cast ceramic parts using the Fickian model. Results showed that higher ceramic loading, higher sample thickness, and lower concentration of the liquid desiccant solution decreased the drying rate. Experiments have been done involving the immersion of green gel cast parts in an aqueous or nonaqueous solution of PEG1000 as liquid desiccant [83]. Cracking, bending, and warping, which are the common defects during conventional drying methods, were eliminated by using this method, and drying time was reduced by about 10 times. An aqueous solution of the liquid desiccant could achieve more homogeneous drying. However, drying rate in an aqueous solution of PEG1000 was lower than that of a nonaqueous solution.

Zheng *et al*. [84] used the liquid desiccant method for drying $BaTiO_3$-based semi-conducting ceramic gel cast parts. The gel cast parts were immersed in the liquid desiccant. The removal of water from the gel cast 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 gel cast parts to more than 45% (in volume) would reduce the stresses developed during drying, and a higher concentration of the liquid desiccant would not induce any defects and would produce a smooth surface ceramic. However, the part with lower thickness and higher solid content in the gel would increase the ceramic density. The gel cast parts could be dried safely at room conditions or in an oven just after the critical stage of drying process of liquid desiccant.

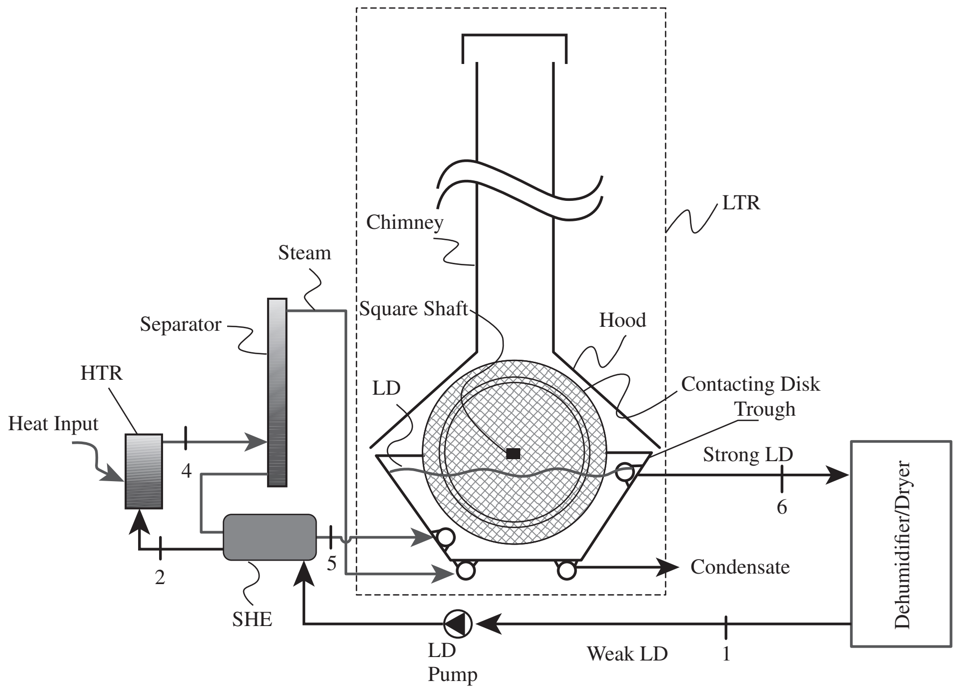


Figure 1.9 LDBD with two-stage regenerator [81]

Trunec [85] conducted osmotic drying of gel cast alumina in water solutions of polyethylene glycol (PEG) with different molecular weights in the range of 1000–80 000 g/mol. Results showed that the PEG solution with highest molecular weight was the most efficient liquid desiccant. Up to 30% water content from gel cast bodies immersed in a 43% (by mass) solution of PEG 80 000 could be removed. Uniform and crack-free drying could be achieved by osmotic drying in the PEG solution with a high molecular weight.

1.2.2.3 Solid vs. Liquid Desiccant Drying System

Figure 1.10 presents the classification of the desiccant-based dehumidification system. The solid desiccant is more widely used in drying applications compared to liquid desiccant. This is because the solid desiccant requires simple construction of drying system. Most of the solid desiccant is designed in the form of rotary wheel beds. In contrast to the solid desiccant, the liquid desiccant has a lower regeneration temperature and a higher moisture removal capacity. Other advantages of using the liquid desiccants in a drying system also include continuous drying even during off-sunshine hours, more uniform drying, and easier humidity control. However, the liquid entrainment in the processed air and the corrosion of the desiccant salt are the main challenges for the practical use of the liquid desiccants. The hybrid-based system is the combination of solid or liquid desiccant materials, which may have the advantages of both.

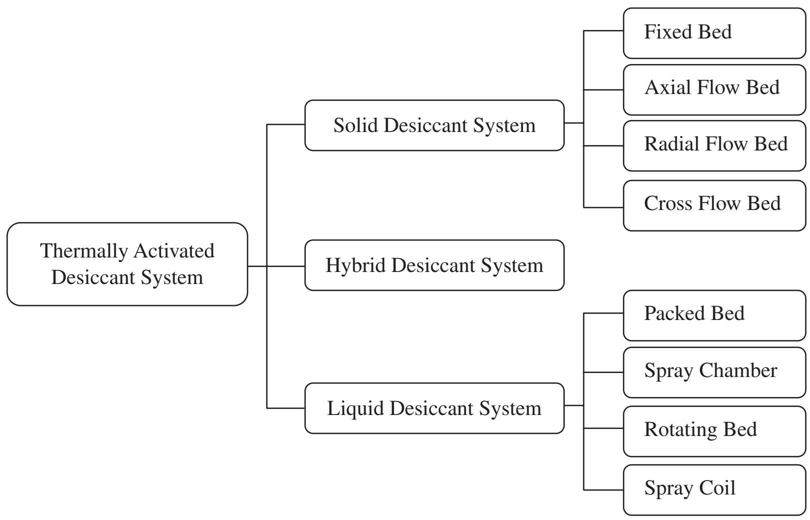


Figure 1.10 Classifications desiccant dehumidification system

1.2.3 Regeneration Methods

Desiccants work based on the principle of moisture transfer due to the difference of vapor pressure between the air and the desiccant. The cool desiccant with low moisture content will adsorb moisture from air until its vapor pressure is in equilibrium with the air. The regeneration of desiccant is actually a process of moisture removal from the desiccant (i.e., a drying or dehydrating process), which happens when the vapor pressure on the desiccant surface is higher than the surrounding air. Overall, the regeneration methods can be categorized into two groups: the heating method and the nonheating method. The heating method mainly uses electrical heater, waste heat, solar energy, heat pump or microwave radiation, and the nonheating method may employ membrane osmosis, electro osmosis, pulsed corona plasma, or ultrasound. The nonheating regeneration methods can help to reduce the regeneration temperature of desiccants and improve the energy performance of the dehumidification system. Therefore, they have been noted by people in recent years.

1.2.3.1 Heating Method

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 [86] studied the efficiency of a desiccant wheel system in which the heater was used for the regeneration (as shown in Figure 1.11). The study showed that the adiabatic efficiency of the desiccant wheel mainly depended on dehumidification and

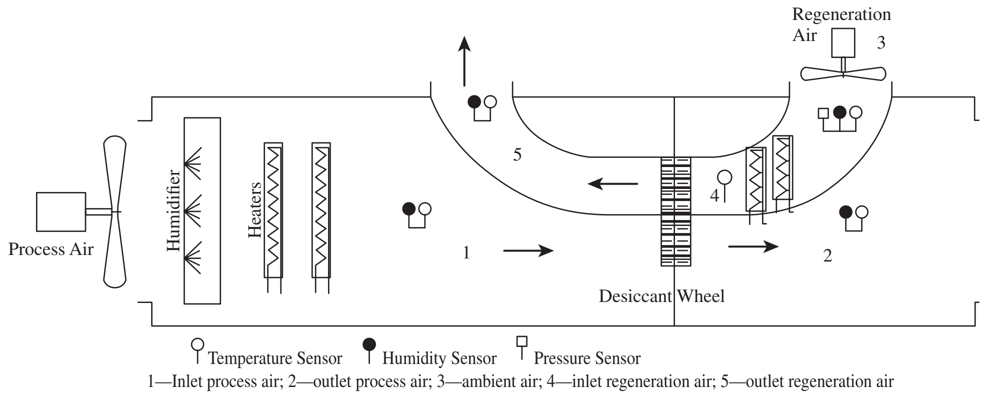


Figure 1.11 Desiccant wheel experimental setup [86]

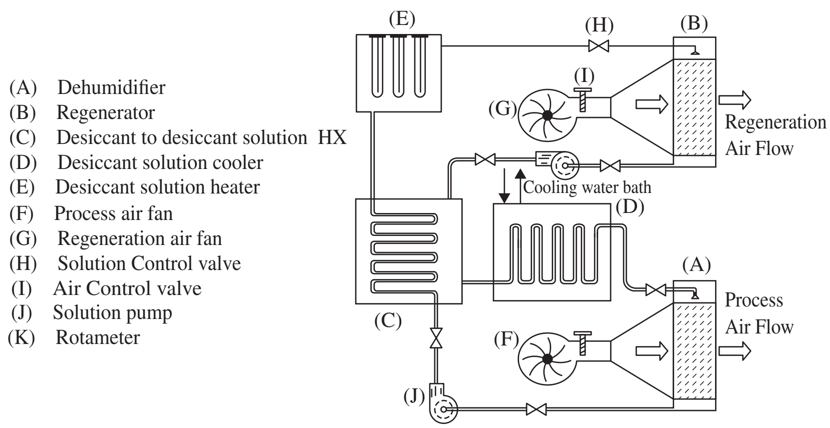


Figure 1.12 Cross flow liquid desiccant dehumidification system [87]

regeneration efficiency, and it increased when the desiccant wheel speed was increased from 4 to 24 rev/h.

Bassuoni [87] designed a cross flow liquid desiccant dehumidification system (as shown in Figure 1.12) and investigated the performance of the structured packing cross flow air−liquid desiccant contacting surfaces on the dehumidification and regeneration of the system. In the dehumidification system, an electric heater was used to heat the liquid desiccant for the regeneration.

Waste Heat

The utilization of waste heat for the regeneration in a desiccant dehumidifier system is one of the best alternatives because it can reduce the cost for the regeneration. However, it is only suitable for occasions where the exhaust waste heat at temperatures between 60 and 140 °C can be available.

The US Department of Energy (DOE) developed the Integrated Energy System (IES), which aimed at improving the overall energy efficiency of distributed generation (DG) systems. The system was integrated with the waste heat recovery and thermally activated (TA) technologies [88]. The TA technology used the hot exhaust gas of the DG system to heat, cool, and regenerate the desiccants in the dehumidification systems. The exhaust gas from the DG system could be used directly or routed to a heat recovery unit (HRU) through an air-to-water heat exchanger. The micro turbine generator (MTG) could be operated individually or integrated with various waste heat recovery. The overall efficiency of IES increased from 5 to 7% when used with an exhaust-fired desiccant dehumidification unit.

Solar Energy

The use of solar energy for the process of regenerating desiccant material has been studied extensively since it is a free energy source. The initial cost of a solar collector system is not very cheap. The payback period must be fully considered during the utilization of solar energy. In addition, 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*. [89] developed two solar desiccant dehumidification regeneration systems known as SDERC (Solar Dehumidification and Enhanced Radiative Cooling) and SRAD (Solar Regeneration and Dehumidification). The SDERC system mainly consisted 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 was depicted in Figure 1.13. During the night, indoor air flowed through the solid desiccant bed and then through an evaporative cooler to decrease the temperature before it returned to the house. During the daytime, solar energy heated the glazed chamber and air passed through the saturated desiccant for the regeneration process.

Xiong *et al*. [90] studied a two-stage solar-powered liquid desiccant dehumidification system with two types of desiccant solutions (as shown in Figure 1.14). In this system, the air was

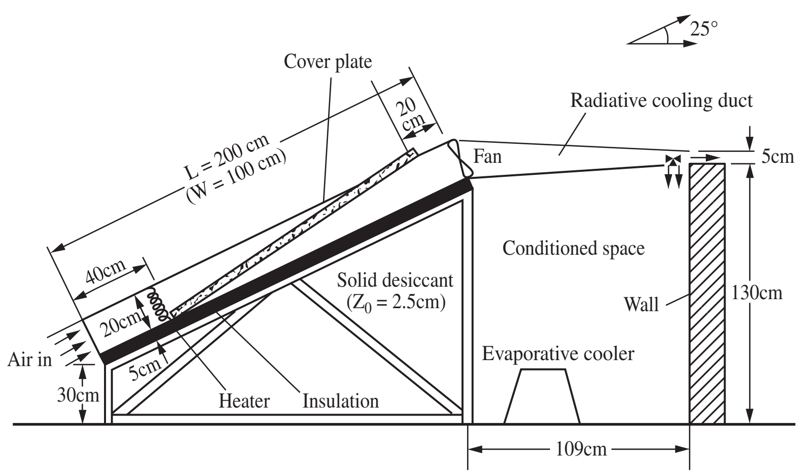


Figure 1.13 Installation of SDERC system [88]

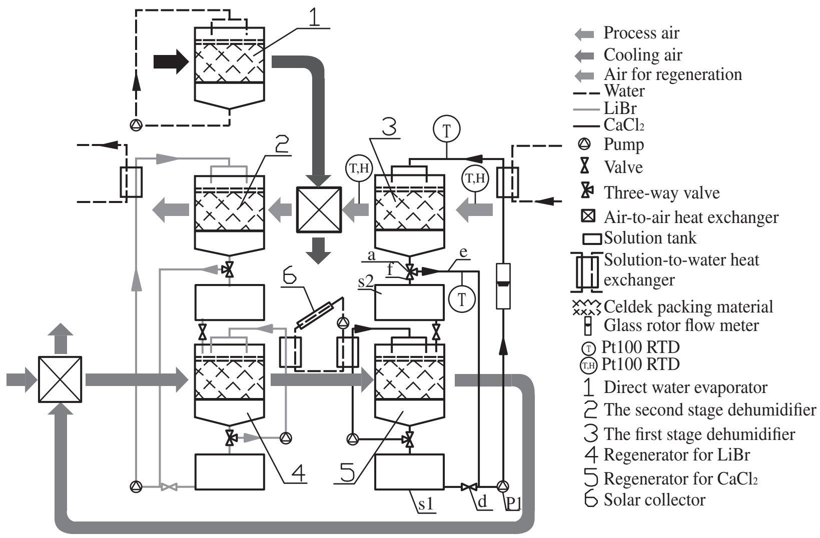


Figure 1.14 Two stage liquid desiccant [89]

dehumidified 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.

Alosaimy and Hamed [91] used a flat plate solar water heater to regenerate the liquid desiccants. The system mainly included a solar water heater with a storage tank, a water-to-air heat exchanger, and a packing of a honeycomb type (as shown in Figure 1.15). 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 could regenerate up to 50% of the solution at 30% solution concentration.

Heat Pump

Heat pump is considered as an energy-efficient dryer system due to its low energy consumption. The combination of heat pump system and desiccant system in the drying applications 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 conditions at low energy consumption.

Wang *et al*. [92] designed and developed a hybrid system combining heat pump and desiccant wheel (as shown in Figure 1.16) to produce low-cost drying and supply low DPTs of air. This system was used for rapid surface drying to avoid re-condensation at low DPT and low dry-ball temperatures (DBTs) in the range of 10–20 and 20–30 °C, respectively, after the product was dried. The heat rejected by the condenser was used to regenerate the desiccant wheel. Moisture from the ambient air was removed in a dehumidification process by condensation from the evaporator and adsorption using the solid desiccants.

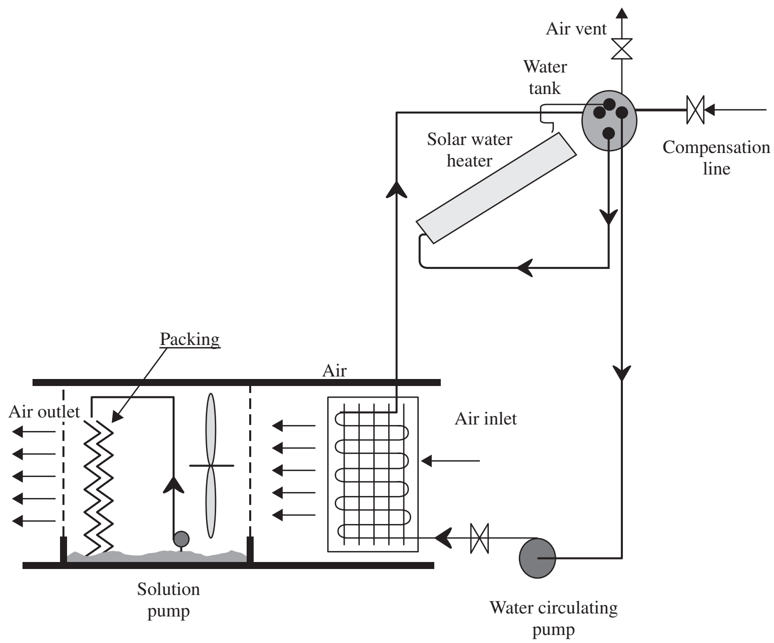


Figure 1.15 Regeneration of liquid desiccant by solar energy [90]

Microwave Radiation

In the conventional heating method, the hot air is usually employed as a heating medium for the desiccant regeneration. However, hot-air heating requires a long time to heat the entire desiccant rotor, because thermal energy is indirectly transferred from hot air to the rotor. Moreover, it is well known that lowering the regeneration temperature, especially below 80 °C, leads to a significant decrease in the humidity control performance due to insufficient water desorption. Microwave irradiation supplies energy to the whole material body, allowing the materials to produce thermal energy. As a consequence, the temperature of the materials rises rapidly. Based on the merits of microwave irradiation, a novel hybrid regeneration process combining microwave and conventional hot air (HA) heating has been proposed by some researchers [93–98]. Combination of both heating methods is expected to achieve higher regeneration rate due to the direct and rapid heating by microwave irradiation in addition to indirect heating by hot-air flow, and it will promote the utilization of the low-temperature thermal energy.

A desiccant wheel system with the microwave-assisted regeneration was designed and investigated by Mitsuhiro *et al*. [97, 98]. The system mainly consisted of a microwave irradiator, circular wave guide, microwave dummy load, desiccant rotor, and electric heater (as shown in Figure 1.17). The desiccant rotor coated with synthesized zeolite was used and installed inside the aluminum waveguide. Microwave energy was supplied from an irradiator through a horizontal circular waveguide, and was finally absorbed by circulating water flow. The regeneration characteristics of the desiccant rotor were experimentally investigated under conditions of microwave heating, hot-air heating, and combined heating at various microwave powers

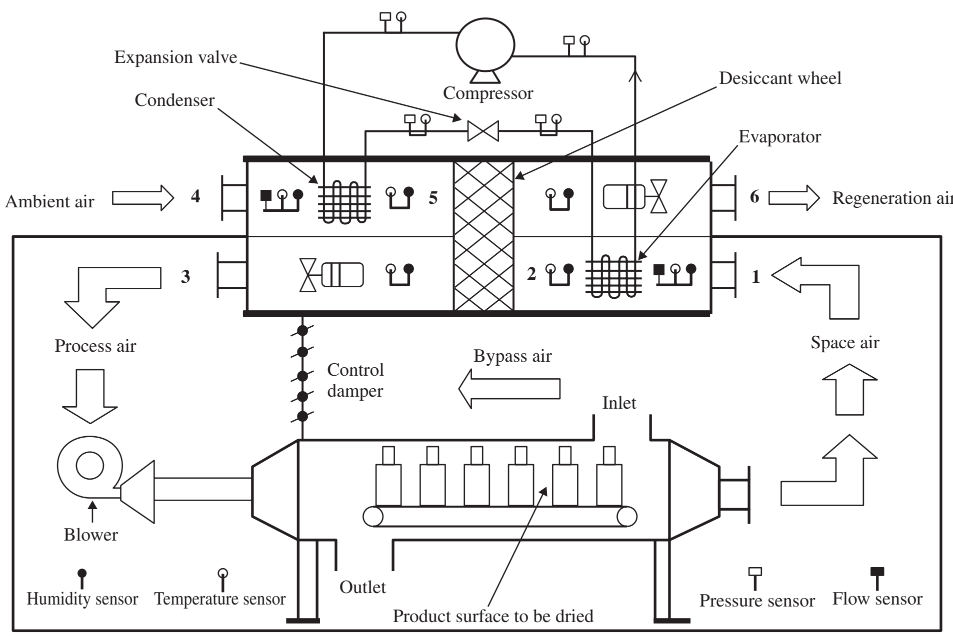


Figure 1.16 Hybrid desiccant system [91]

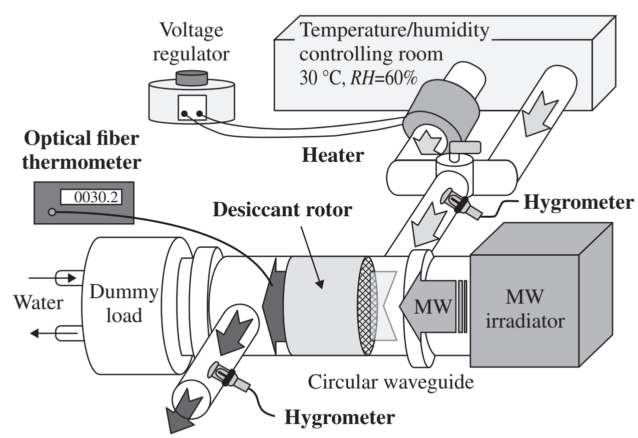


Figure 1.17 Desiccant wheel with microwave-assisted regeneration [92]

and hot-air temperatures. The study showed that the combined heating was effective for leveling nonuniform temperature distribution in the rotor, and the combined heating could acquire a larger regeneration rate and regeneration degree compared with the either microwave or hot-air heating. By applying the combined and microwave heating method to the dehumidification systems could reduce the switch time between the adsorption and the regeneration of the desiccant.

1.2.3.2 Nonheating Method

Membrane Osmosis

Osmosis is a process in which the solvent is transported through the membrane as a result of a difference in trans-membrane concentration. If the system is not subjected to any external influence, such removal of excess solvent results in the establishment of a hydrostatic pressure difference. The reverse osmosis process is characterized by the use of pressure in excess of the osmotic pressure to force the solution of salt at the same temperature through a selective membrane capable of rejecting the dissolved salts. The process name is derived from the phenomenon whereby the water under an applied pressure driving force flows in the opposite direction to that normally observed in an osmotic process where the driving force is the concentration gradient [99].

Reverse osmosis (RO) has been successfully applied to desalination of seawater in which saline water with some concentration of dissolved salts is distilled into pure water when passed through a membrane. In a similar manner, weak desiccants (e.g., calcium chloride and lithium chloride) may be distilled by removing the water from the solution with a suitable membrane [100].

Al-Sulaiman *et al*. [101] studied the energy performance of a cooling system with two-stage evaporative coolers using liquid desiccant dehumidifier between the stages (as shown in Figure 1.18). The reverse osmosis process was used for regeneration by mechanical energy, and an MFI zeolite membrane was proposed for separation of water from the weak desiccant solution. The osmotic pressure that separated product water from the weak calcium chloride solution under equilibrium conditions was found to be 24.4 MPa. Obviously, the major energy requirement associated with this cooling system is the energy for regenerating the weak liquid desiccant.

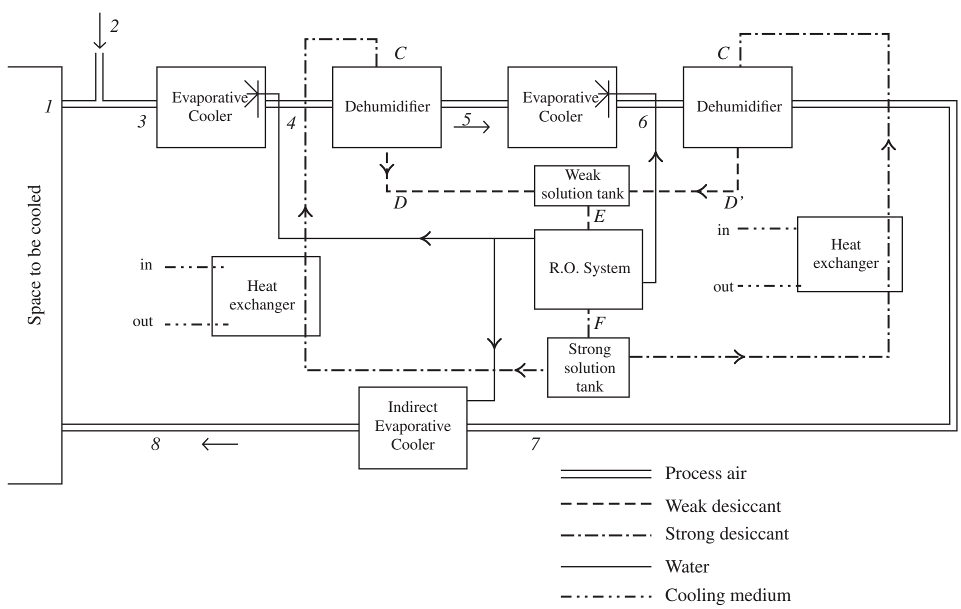


Figure 1.18 Schematic for liquid desiccant cooling system using RO regeneration [98]

A thermally driven flat plate air gap membrane distillation liquid desiccant regenerator for lithium chloride in dehumidification applications has been theoretically modeled by Alexander *et al*. [102]. According to the model results, the regenerator with membrane materials removed 11.4 g/(min·cm^3) of moisture with a COP (coefficient of performance) of 0.372 for the inlet solution concentration of 0.38, the solution flow rate of 50 ml/min, and the heated solution temperature of 135 °C.

Electro Osmosis

EO (electro-osmosis) flow is a flow in porous media or micro-channel structure, driven by the so-called EO force with an applied electrical field. The EOF (electro-osmosis force) dynamics in porous media have been well studied both theoretically and numerically. For most types of EO flow, an electric double layer (EDL) will be formed spontaneously at the liquid/solid interface due to electrochemical reaction. As depicted in Figure 1.19 [14], when contacting with an electrolyte (water in the regeneration system), the Si–O on the internal surfaces of the porous solid desiccant dissociates to act on regions of net charge. A layer of ions is firmly absorbed to the surface of the solid and does not move in the electric field applied, which is called a compact layer. And an equal number of opposite ions, which is called the diffuse layer, is in a liquid water state and less attracted to the surface. These two layers form the EDL [103]. The density of ions reduces as the distance from the surface increases, and so does the potential. The potential in shear plane of the two layers is called zeta potential [104], and it is negative for the solid desiccants. Once an electric field is supplied to the EDL, cations of the diffuse layer are driven by the Coulomb force from the anode to cathode so that the liquid in this area flows with the ions [105]. The fluid outside the EDL travels completely dependent on the viscous force. It therefore forms the EO flow which travels from the anode to cathode. The solid desiccant, which has both electro-osmosis and adsorption characteristics, adsorbs moisture from the moist air, and the water vapor turns into liquid water on the surfaces of

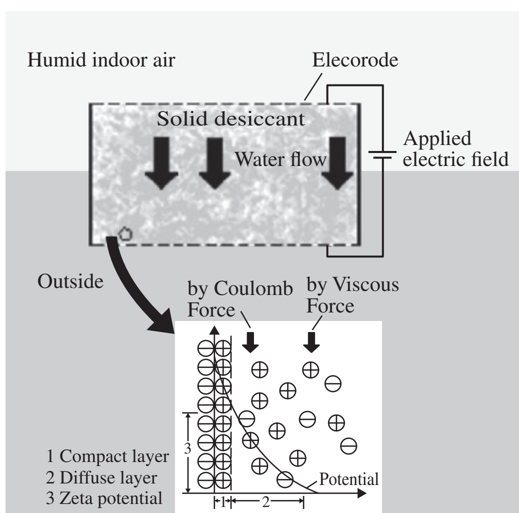


Figure 1.19 Schematic of the principle of the EO regeneration method [101]

the material. Then, with the effect of an electric field, the electro-osmosis transports the water away and the material could continue adsorbing the water vapor in the air.

Possible improvement methods for EO regeneration have been investigated by Qi and Tan *et al*. [15]. These include changing the anode material, changing the cathode layout, applying interrupted power, and optimizing electrical field strength. Through detailed experiments and analysis, it was found that applying platinum-plated titanium mesh as an anode could improve the working lifetime from 6 to over 120 hours and effectively reduce the Joule heating effect simultaneously; laying a piece of filter cloth under the cathode could enhance the EO regeneration rate up to 0.0021 g/s; the application of interrupted power could increase the regeneration rate by up to 1.5 times; the optimal on-off-time was found at 30 seconds : 1.3 seconds with 17 V/cm electric field strength and 30 seconds : 0.8 seconds with 11 V/cm; and the most suitable value of electric field strength was observed as ranging from 8.5 to 13 V/cm in the EO regeneration system.

Li *et al*. [106] also investigated the method of electro-osmosis based regeneration for a solid desiccant and its potential application in the HVAC (Heating, Ventilation and Air Conditioning) field, particularly for the dehumidification process in an air-conditioning system. The energy consumption in an EO integrated air-conditioning system was found to be averagely 23.3% lower than the conventional air-conditioning system with respect to different configurations in the air handling process.

Although the electro-osmotic regeneration for the solid desiccant has been proved to have many merits, such as regeneration without the heat source, energy-saving, and simple structure [14], it is still at the experimental stage.

Pulsed Corona Plasma

The concept of nonthermal plasma desorption or regeneration was first investigated by using methyl ethyl ketone (MEK, $CH_3CH_2COCH_3$) [12], and then the concept of plasma desorption was further demonstrated with benzene [107] and NO_x [108]. The mechanism of plasma desorption is thought to be due to the impact of high-energy electrons and excited molecules, or possibly electrostatic attraction among the ionized molecules adsorbed on the adsorbent and ionized background molecules. This mechanism might occur because the gas molecules are not chemically but physically bonded to the adsorbent [109]. The use of the nonthermal plasma may have several advantages; for example, the system can be operated at room temperature and atmospheric pressure, and it does not generate excessive heat.

Yamamoto *et al*. [13] investigated the characteristics of nonthermal plasma desorption with the experimental setup shown in Figure 1.20. The moist air passed through the reactor, where water vapor adsorption material and the plasma desorption unit were placed. The moisture concentration was measured both inside and outside the reactor by using a photo-acoustic, single-gas monitor analyzer. The adsorption material was placed between the multiple needles and perforated plate electrodes. The experimental results showed that the water vapor desorption per unit power (energy efficiency for desorption) and the desorption rate (or the gradient of desorption) for the nonthermal plasma was superior to that of conventional thermal desorption.

Ultrasonic Radiation

In recent years, a lot of research has been done on the nonheating method by using ultrasonic technology. A series of studies have proved that the ultrasound-assisted regeneration could significantly improve the dehydration kinetics of desiccants and energy efficiency [22–42].

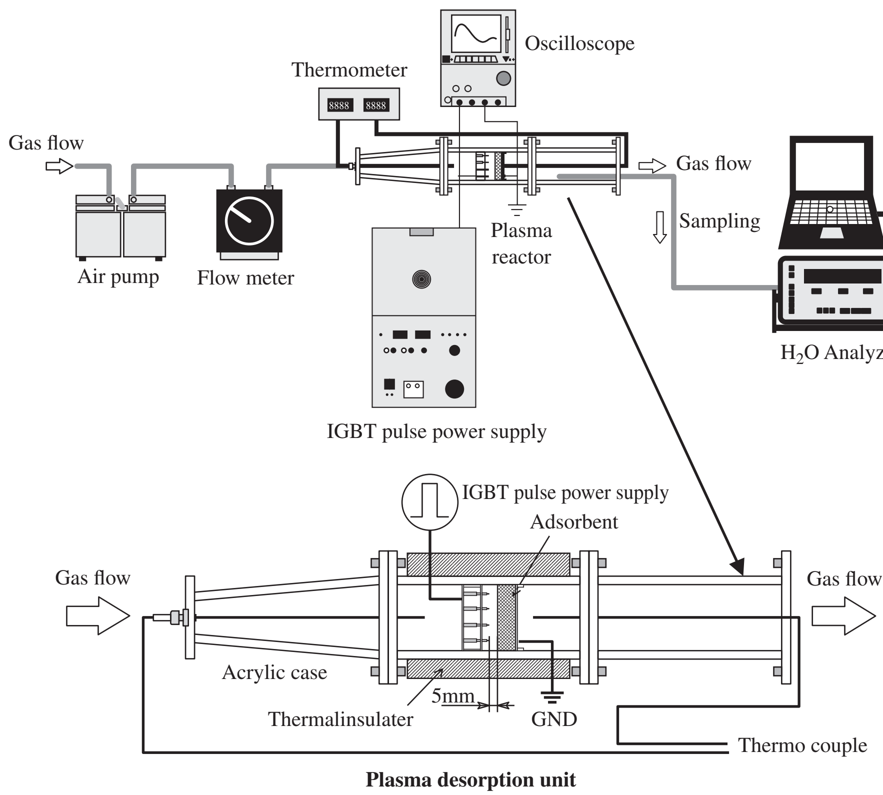


Figure 1.20 Experimental setup for water vapor adsorption and desorption [14]

Meanwhile, several Chinese invention patents have been proposed for the applications of the new regeneration technology in practical engineering [31–37]. These study results will be presented in detail in the following chapters.

1.3 The Proposed Method

1.3.1 Basic Knowledge about Ultrasound

Sound is a special form of energy transmitted through pressure fluctuations in air, water, or other elastic media. Any displacement of a particle of this elastic medium from its mean position results in an instantaneous increase in pressure. When leveling, this pressure peak not only restores the particle to its original position but also passes on the disturbance to the next particle. The cycles of pressure increase (compression) and decrease (rarefaction) propagate through the medium as a sound wave. Ultrasound is an oscillating sound pressure wave with a frequency greater than the upper limit of the human hearing range. Ultrasound is thus not separated from “normal” (audible) sound based on differences in physical properties, only the fact that humans cannot hear it. Although this limit varies from person to person, it is

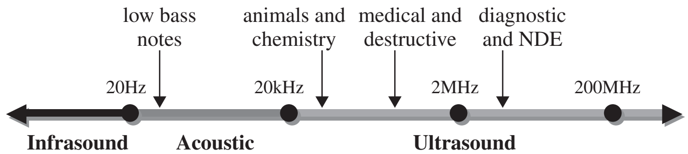


Figure 1.21 Approximate frequency ranges corresponding to ultrasound [13]

approximately 20 kHz in healthy, young adults. Ultrasound devices operate with frequencies from 20 kHz up to several gigahertz (as shown in Figure 1.21) [110].

On a micro scale, sound is characterized by pressure (p_{sound}) and particle velocity (u_{sound}). The product of these two parameters is called sound intensity (I_{sound}) – a vector normal to the direction of sound propagation:

$$I_{\text{sound}} = p_{\text{sound}} \times u_{\text{sound}} = \frac{Force}{Area} \times \frac{Distance}{Time} = \frac{Energy}{Area \times Time} = \frac{Power}{Area} \tag{1.1}$$

As shown in Figure 1.22, sound generated by a point source with power W propagates as a spherical wave. Therefore, sound intensity is inversely proportional to the square of the distance from the sound source. The variations of both pressure and velocity follow a sinusoid; if they are in phase, the peak pressure occurs at the same time as the peak in the particle velocity, and the product of these two gives the intensity, which is not only the maximum instantaneous intensity but also the maximum time-averaged intensity.

On a macro scale, sound is primarily characterized by the frequency (f), which relates the speed of wave propagation (u) (sound velocity) to the wavelength (λ):

$$f = \frac{u}{\lambda} \tag{1.2}$$

The second main quantity used to characterize sound on a macro scale is the amplitude of sound pressure level (SPL) on the decibel (dB) scale which takes 20 μPa as the reference level.

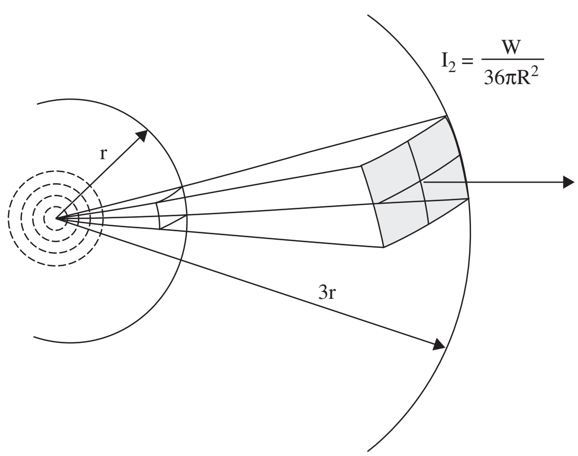


Figure 1.22 Sound intensity around the point source of acoustic energy

In a free acoustic field such as in an open air or anechoic chamber, the pressure and intensity levels in the direction of propagation are many times more than which travels in all directions with equal magnitude and probability (reverberation chamber). The pressure and intensity levels are different, and this difference is known as the pressure-intensity index. Aside from the frequency and sound intensity, another key point for the acoustic applications (e.g., sound-assisted dryers) is the mode of energy propagation. Sound energy can be propagated as longitudinal waves (also called compression waves) or transverse waves in which vibration of the particle in the material occurs perpendicularly to the direction of wave motion. Since the latter cannot be propagated in gases and liquids except for highly viscous liquids over very short distances (fraction of a millimeter), sound-assisted dryers are normally designed to accommodate longitudinal waves [111].

In a free space, the sound source can be considered as a point source. In practical industrial applications, however, sound is either shapes such as horn, paraboloid, and ellipsoid. In both cases, such sound radiation can be regarded as coming from a plane source. This results in a constant sound intensity (the Fresnel zone), whereas outside this zone (the Fraunhofer zone), the sound intensity decreases inversely with the square of the distance from the plane source, that is, in the same way as for a point source (as shown in Figure 1.23). The length of zones and the sound intensity distribution may be crucial for the configurations of sound-assisted dryers. The Fresnel zone for the plane source 10 cm in diameter is negligible (a couple of millimeters) for sound at 100 Hz (cf., frequency of pulse combustion), but extends for 15.6 cm in the range of ultrasound at 20 kHz and 31.2 cm at 40 kHz. According to the frequency of pressure pulsation, sound can be classified as infrasound ($f < 20$ Hz), sound (audible) (20 Hz $< f <$ 20 kHz), and ultrasound ($f >$ 20 kHz).

Ultrasonic applications are rigidly classified into low- and high-intensity applications. Low-intensity applications are made typically in the megahertz frequencies and acoustic power up to tens of milliwatts and usually do not alter material properties under operation. In contrast, high-intensity ultrasound is generally used for changing the properties of the material through which it is passed or altering the physical–chemical processes. High-intensity applications are made at low frequencies (i.e., from 20 to 40 kHz), and these are usually used in drying and dewatering.

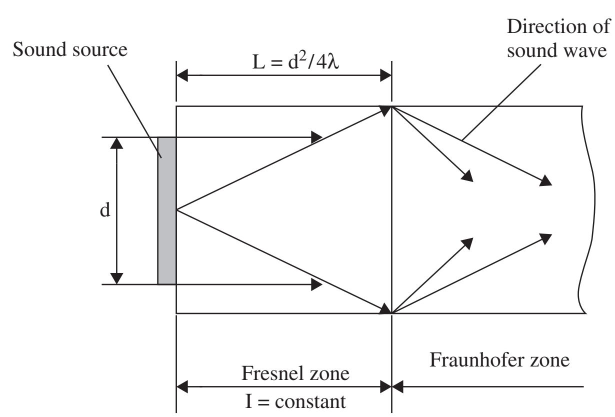


Figure 1.23 Propagation pattern from a plane sound source [111]

In the case of a plane progressive wave penetrating the material being dried, the sound energy is attenuated due to various mechanisms including relaxation processes, viscous shearing effects, and molecular absorption. Neglecting the scattering of sound energy, the amplitude of acoustic pressure at a distance x from the material surface at which the incident sound pressure is p_o may be expressed as:

$$p(x) = p_o \exp(-\alpha x) \tag{1.3}$$

where, α is the attenuation coefficient, which is a function of material properties and sound frequency, and it is often determined experimentally.

Equation (1.3) can be written conveniently in terms of sound intensity, which reflects the energy flux per unit surface area:

$$I = \frac{p^2}{u\rho} \tag{1.4}$$

where ρ is the material density and u the sound velocity. Hence,

$$I(x) = I_o \exp(-2\alpha x) \tag{1.5}$$

Assuming no heat loss from the absorbing volume, the rate of temperature rise is given by

$$\frac{\mathrm{d}t}{\mathrm{d}\tau} = \frac{2\alpha I}{\rho c} \tag{1.6}$$

where, t is temperature of medium, °C; τ is time, s; c is the specific heat of material, J/(kg·°C).

1.3.2 Sound Generation

In industrial applications, sound waves are generated by a transducer, which converts the original form of energy to the energy of oscillatory motion. Such transducers are classified into five main groups [112]:

1. Piezoelectric. The periodic changes in the physical size of certain crystals (such as quartz, tourmaline, and zinc oxide) due to applied electric potential generate mechanical vibrations that are propagated as sound waves. Used in the range from 20 kHz to 10 GHz.
2. Magnetostrictive. Mechanical vibrations are caused by changes in the physical size of certain metals such as nickel, cobalt, and iron, or certain nonmetals known as ferrites due to an external magnetic field. Used in the range of 40–100 kHz.
3. Electromagnetic. The vibration of a solid armature (e.g., membrane in loudspeakers and microphones) is due to coupled electric and magnetic fields. Used at $f < 50$ kHz.
4. Electrostatic. The periodic variation of charges in an electrical capacitor of a special design induces mechanical vibration. Used at $f < 100$ kHz.
5. Mechanical. Sound waves are generated due to the action of a truly mechanical device such as rotating counterbalanced weights or a mechanical device energized by the kinetic energy of the working fluid (sirens and whistles). Used at $f < 50$ kHz.

For high-intensity generation and propagation of sound in gases at frequencies up to about 25 kHz, mechanical generators are used almost exclusively because of their design and operational simplicity, energy capability, and low cost as compared to the other types of

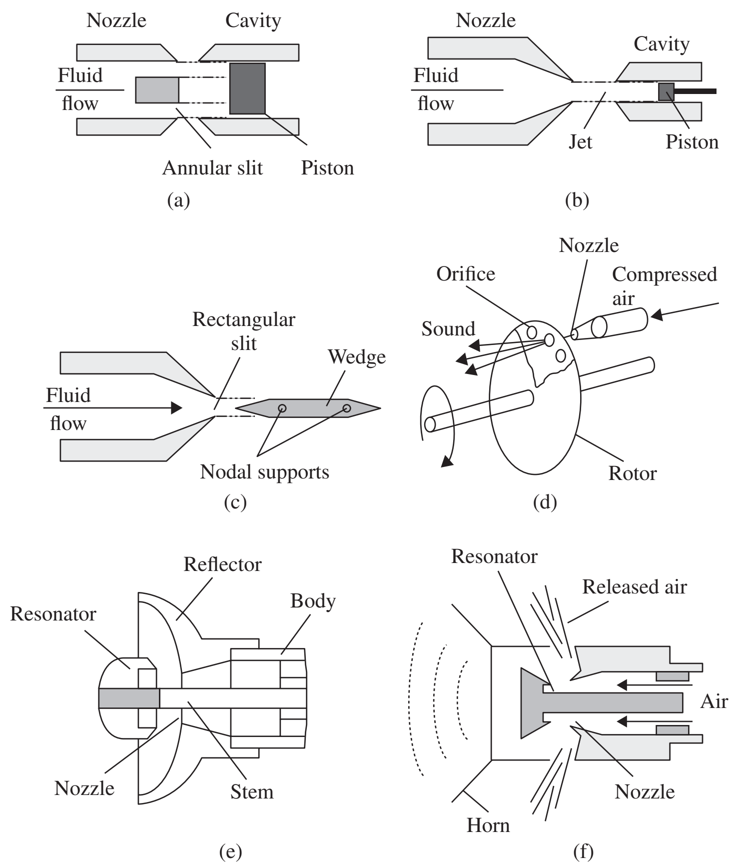


Figure 1.24 Principles of sound generation in mechanical sound generators [111]. (a) Galton whistle, (b) Hartman whistle, (c) wedge resonator, (d) dynamic siren, (e) modified Hartman whistle, and (f) Branson sound generator

transducers. These generators that produce the so-called *airborne sound* are used in sound and sound-assisted convective drying. Figure 1.24 presents the most frequently used types of mechanical generators from the group of cavity resonators (Galton and Hartman whistles), wedge resonators, and sirens. Usually, in a modified Hartman whistle, a rod is centrally positioned along the axis of the gas jet. Such a design allows for a more compact generator of increased efficiency. In the Branson pneumatic sound generator, the exhaust air jet is separated from the sound field, which does not only result in a higher sound intensity (no air turbulence effect) but also the generator to be used in processing materials for which contact with air is not acceptable. One of the possible designs of industrial sound generators is shown in Figure 1.25. When rotated at 4000–9000 rpm and fed with 0.138 m^3/s of compressed air at 0.3–0.5 MPa, this dynamic siren ($d = 0.2$ m) emits sound up to 180 dB and 8 kW of acoustic power [113].

In processing of liquid systems such as dewatering of slurries and pasty materials, piezoelectric, or magnetostrictive generators are used. The active part of such a generator (called a driver) generates and transmits mechanical vibrations through a solid rod (a booster) to

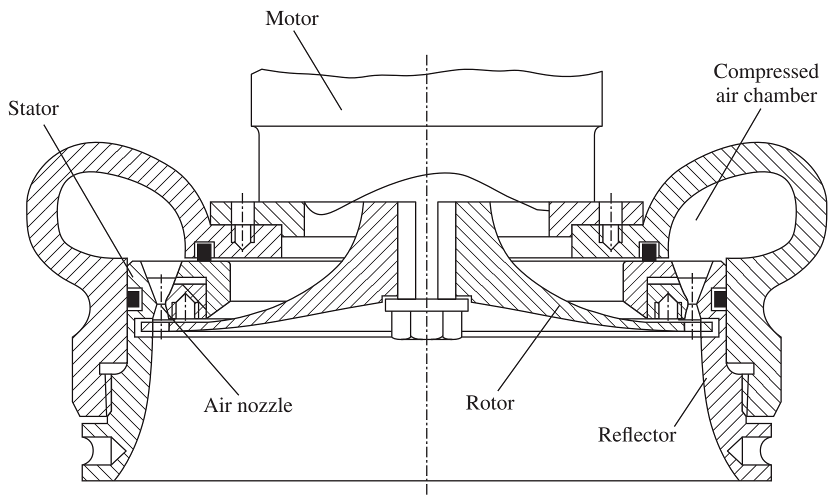


Figure 1.25 Design of a pneumatic sound generator [111]

the metal profile (a horn). This horn serves as an amplitude transformer to amplify the displacement of the driver and to match the transducer impedance with the impedance of the material to be processed. The mechanical vibrations from the horn are further coupled to the processed material either directly (the horn is inserted into a liquid or pasty material) or indirectly through a membrane.

1.3.3 Fundamental Theory for Ultrasound-Assisted Regeneration

Since the desiccant regeneration is essentially a heat and mass transfer process, the theory of ultrasonic-assisted regeneration may be illustrated by the following possible mechanisms of heat-and-mass-transfer alterations in an ultrasonic field:

1. Alternating compression and expansion due to high-frequency pressure pulsation create surface cavitation that breaks the boundary layer and allows liquid to evaporate under partial vacuum [114].
2. Intensive circulation flows (induced by sound pressure) on the drying surface promote surface evaporation [115].
3. Pressure pulses from the sound waves increase the turbulence which reduces the thickness of the laminar sublayer [116].
4. An increase in moisture diffusivity and a decrease in viscosity [117].
5. A pulsating partial vacuum transmitted into the material affects water vapor transport, possibly by decreasing or overcoming the attraction forces between the water and solid molecules; Shear reduction in boundary film surrounding the material [118].
6. Expansion of the vapor bubbles inside capillaries yields a migration of the water filament (sonic diffusion current) [119].
7. Increase in the bulk temperature due to the acoustic energy dissipation, also called "thermal effect" [120].

The data from the review of literature indicates that cavitation enhanced turbulence of the gas phase at the solid (or liquid droplet) surface and mechanical effects due to internal stresses appear to be the major contributors to enhanced moisture removal during drying. It is also reasonable to expect the liquid viscosity to be lowered in ultrasonic fields, which promotes diffusion of moisture toward the evaporation surface. The term cavitation in general refers to the formation and subsequent dynamic behavior of vapor bubbles in liquids. Acoustic cavitation occurs when high-intensity sound waves are coupled to the liquid surface, which results in the propagation of alternating regions of compression and expansion, and thus in the formation of micron-size vapor bubbles. If the bubbles are of a critical size (determined by acoustic frequency), they may implode violently, releasing energy in the form of impulses ($t < 0.1$ second) with local point temperature and pressure in the order of 5000 K and 1000 atm, respectively [121]. Since the effective temperature zone is confined to about 0.2 m from the surface of the collapsing bubble, the bulk of the liquid remains practically at the same temperature. However, as the bubbles at or near the surface implode, micron-size liquid droplets can be released into the surrounding air and evaporated instantaneously. Because of the cavitation threshold, larger acoustic pressure amplitudes at a given frequency are required for highly viscous liquids.

It is reasonable to assume that pressure fluctuation caused by sound waves disrupts the boundary layer at the solid or liquid surface, so that they should affect the inter-phase transfer rates and thereby accelerating drying rates. In fact, a substantial decrease (up to 15%) in the boundary layer thickness has been found when conventional spray drying of blood plasma was complemented by high-intensity sound at $f = 15$ kHz and $I = 155$ dB [116].

Aside from cavitation, the enhanced mass-transfer rates in acoustic fields can be attributed to the plug flow of the capillary liquid as well as to the enhanced dispersion of the liquid and vapor moisture due to alternating compression and expansion cycles, which result in reduced viscosity of the liquid–vapor mixture. In fact, a substantial increase in the amount of liquid diffusing through porous solids has been noted in the presence of ultrasound [122]. The enhanced diffusion appears to be of the directional type as mass transfer was hindered when ultrasound irradiation was opposed to the direction of diffusive flow [123].

According to Kardashev [124], the mechanism of acoustic drying of capillary-porous materials depends on the level of moisture content. When the material is very wet (200–500%), the effect of an ultrasound field is truly mechanical, and moisture is removed due to better dispersion of liquid water, especially at the antinodes of a standing wave. When the material moisture content is much lower (10–70%), but drying takes place during the constant-rate period, the sound waves reduce the thickness of the boundary layer, which alters moisture evaporation. In the falling rate period, the sound waves enhance only the moisture diffusivity due to temperature rise because the sonic energy is dissipated as heat. In the case of dispersed materials, the positive effect of sound waves on a drying rate appears for the SPL above a certain threshold value.

Under real drying conditions, heat generated within the material volume is transported away by conduction and convection; hence, the final equilibrium temperature tends to be determined by the heat balance. The equilibrium temperature for the bulk of the material is in the order of a few degrees [125], which justifies moisture evaporation due to thermal effects of sound irradiation to be neglected. This obviously favors sonic drying as a method for processing heat-sensitive materials. Considering heat generation on the micro scale, thermal effects may become important as the localized temperature increase is likely to affect fluid properties and solid–fluid interactions (e.g., lower surface tension or viscosity). According to the study by

Moy and DiMarco [126], for example, 7% of the sound-enhanced freeze-drying (F-D) rate of liquid food could be attributed to the thermally induced mechanical effects on the gas phase, resulting in friction, and adiabatic compression. Detailed discussions of these and other phenomena activated by the sound energy can be found elsewhere [127, 128].

1.4 Summary

This chapter mainly deals with the background of the topic relevant to this book and the corresponding technologies including desiccant materials, desiccant dryer systems, and regeneration methods based on the literature review. Afterwards, the basic knowledge about ultrasound and the sound generating methods as well as the fundamental theory for ultrasonic-assisted regeneration have been introduced for a better understanding of the novel regeneration method to be illustrated in the following chapters.

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