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Review

A Review: Study on the Enhancement Mechanism of Heat and Moisture Transfer in Deformable Porous Media

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Abstract: The heat and moisture transfer process in deformable porous media commonly exists in material drying, solid waste treatment, bioengineering, and so on. The transfer process is accompanied by deformation of the solid skeleton and pore interface structure, which limits the transfer rate and affects quality. Microwave and ultrasound are the main representatives of reinforcement technology. However, as the moisture decreases, the energy utilization efficiency of microwaves decreases significantly. Based on the experimental and theoretical methods, the enhancement mechanism of ultrasound on the process is studied, which provides guidance for the wide application of ultrasonic enhancement. With the increase in ultrasound power, the pore area and the moisture effective diffusion coefficient gradually increase. A macroscope mathematical model for ultrasonic-coupled thermal-hydro-mechanical modeling is developed, and the results show that ultrasound increases the temperature gradient within material, resulting in higher moisture transmission rates with an ordered direction, and the alternating expansion and compression process results in smaller macroscopic deformations. Subsequently, the drying kinetic characteristics of typical deformable porous media such as municipal sludge, porous fibers, and activated alumina particles are investigated. The process parameters of the ultrasonic assisted drying system are optimized using the response surface method and artificial neural network model.

Keywords: deformable porous media; heat and moisture transfer; irregular shrinkage deformation; microwave; ultrasound

Citation: Li, P.; Ma, C.; Chen, Z.; Wang, H.; Wang, Y.; Bai, H. A Review: Study on the Enhancement Mechanism of Heat and Moisture Transfer in Deformable Porous Media. *Processes* **2023**, *11*, 2699. https://doi.org/10.3390/pr11092699

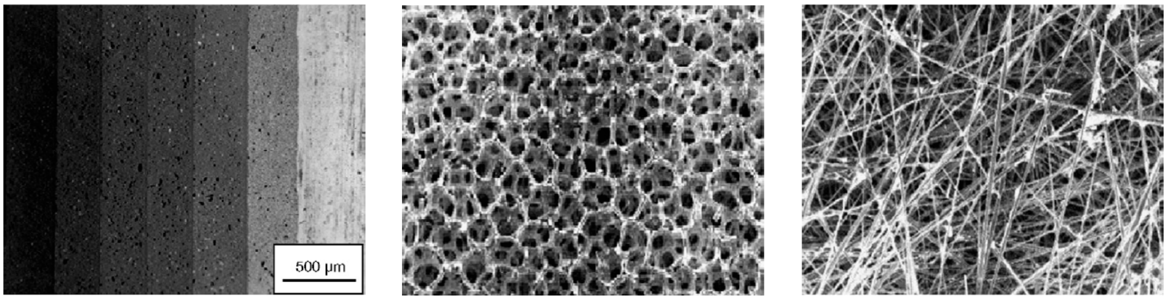
Academic Editor: Ireneusz Zbicinski

Received: 12 August 2023
Revised: 7 September 2023
Accepted: 8 September 2023
Published: 9 September 2023

1. Introduction

During the "14th Five-Year Plan" period, China has embarked on a new journey to comprehensively build a socialist modernized country, with clean and low-carbon development as the leading direction of energy development, promoting green production and consumption of energy. In developed countries, the energy consumption for drying processes accounts for approximately 10–25% of the total national energy consumption, and the average energy utilization rate of the drying industry in the world is generally low [1]. Drying is still a high-energy-consuming operation. Improving drying efficiency and ensuring product quality requires strengthening the heat and mass transfer processes of deformable porous media, which is an important scientific problem currently faced by the engineering thermophysics discipline.

Natural or industrial raw materials are mostly porous media materials, which are a combination of liquid, gas, and solid phases. The solid phase material forms the basic shape of the porous media, which is the solid skeleton. The skeleton is connected to form void space and cavities, which are the pores. Among them, gas and liquid phases serve as filling media for the skeleton, and they jointly occupy the pore space. Due to the complex structure of porous media, as shown in Figure 1, energy and mass transfer inside it is very complicated.



(**a**) (**b**) (**c**)

Figure 1. Three typical porous structures: (**a**) porous open cell foam; (**b**) fiber layer in PEM fuel cell; (**c**) typical cross section in gradient material.

There are many types of porous materials, which can be divided into two categories according to their water absorption characteristics: non-hygroscopic and hygroscopic porous materials [2,3]. For the study of the drying process in non-hygroscopic porous media, the focus is on investigating the laws of various transport phenomena inside the porous media. Most of these studies investigate the relationship between macro-parameters (such as thermal conductivity, porosity, etc.) and permeability, and establish models based on Darcy's law to further analyze and explain some practical phenomena of heat and mass transfer. Significant progress has been made in these aspects of research. Different from non-hygroscopic porous media, hygroscopic porous media will undergo obvious structural shrinkage during the drying process. For hygroscopic porous materials, the heat and mass transfer processes inside the porous media are highly non-uniform, nonlinear, and non-equilibrium. Under the conditions of surface tension and thermal stress, the heat and mass transfer within deformable biological porous media can cause deformation of the solid skeleton and pore interface structure. Therefore, on the basis of studying the internal heat and mass transfer, the structural deformation of hygroscopic porous media during drying will also have an important impact on the heat and mass transfer process, making it difficult to accurately describe its transmission mechanism theoretically and propose effective ways to improve process transmission efficiency. Thermal air drying, microwave drying, and vacuum freeze-drying technology for porous materials are typical representatives. People have developed a series of active or passive enhanced mass transfer technologies to enhance material transfer speed inside porous media and improve relevant production process efficiency.

Currently, a series of active or passive enhanced mass transfer technologies have been studied to enhance the rate of substance transfer in porous media. Significant progress has also been made in the study of heat and mass transfer mechanisms: the heat and moisture transfer of deformable porous media can cause deformation of the solid skeleton and pore structure, with the outer part that loses water first shrinking more than the inner part that loses less water; at the same time, deformation of the organizational structure leads to a decrease in the convective mass transfer coefficient between the surface and hot air as well as the effective diffusion coefficient of moisture inside material.

With the continuous development of external technologies such as electromagnetic fields, ultrasonic fields, and microwaves, people have begun to combine external field-assisted technologies with mass transfer processes, attempting to use the unique mechanical effects, electrochemical effects, and thermal effects of various external fields to enhance mass transfer processes within porous media. The addition of microwave and ultrasonic fields in traditional convective drying processes can enhance the moisture transfer processes within media, which has been proven by many experiments. Therefore, external field-assisted technologies such as microwaves and ultrasonic waves have shown important application prospects in drying, enhanced heat transfer, wastewater treatment, and other areas, attracting widespread attention from the scientific and engineering communities at home and abroad.

2. Study on Heat and Mass Transfer and Shrinkage Deformation Mechanism in Porous Media

2.1. Study on Heat and Mass Transfer Mechanism in Porous Media

Porous media heat and mass transfer phenomena are widely present in human industrial, agricultural, and natural environments. Exploring the mechanisms of heat and mass transfer processes within porous media is of great significance in improving material drying efficiency, analyzing soil thermal and humid environments, developing energy-saving building maintenance materials, and other interdisciplinary fields [4]. Over the past century, researchers both domestically and abroad have developed theoretical models such as energy theory, steam diffusion theory, capillary flow theory, and evaporation-condensation theory to describe the thermal and humid migration process within porous media [5].

In terms of research abroad: Huang [6] analyzed the water transport process in porous media under the effect of temperature gradient and established the mass conservation equation for each component inside the porous medium. Nasrallah and Perre [7] simulated and analyzed the heat and mass transfer process of porous media during convective drying based on volume-averaging theory, applied Darcy's law in the extended form of multiphase flow in porous media, considered the capillary force effect of liquid phase and diffusion behavior of steam, respectively, and established the mass conservation equation and energy conservation equation for the liquid phase, steam phase, and mixed gas phase in porous media. Liesen and Pedersen [8] proposed a mathematical model for the influence of heat and moisture transfer on energy within building structures, used the wet transfer function method to solve the moisture transfer process inside porous media, and solved the wet-heat transfer model using the state-space law of modern control theory. Zambra et al. [9] proposed a non-saturated porous medium heat and mass transfer model, used finite volume method to calculate the heat and mass transfer process of composting under self-heating and oxidation conditions, and analyzed the influence of internal moisture content on temperature and oxygen concentration inside composting.

In terms of domestic research, Wang Buxuan et al. proposed a method in 1987 for determining the thermal and moisture migration characteristics of moist porous media under the third type boundary conditions, which does not require measurement of the transient humidity field and can simultaneously determine the thermophysical properties—thermal conductivity, mass diffusivity, and thermal-mass diffusivity [10]. He Yaling and Xie Tao summarized the development of the calculation model for the equivalent thermal conductivity of nano-porous materials in recent years, providing theoretical guidance for accurately establishing heat transfer calculation models of aerogels and other nano-porous materials, as well as predicting and optimizing the performance of nano-porous insulation materials [11]. Sun Zhen et al. developed a porous capillary evaporation/boiling heat transfer model, which can effectively predict the heat transfer efficiency of capillaries in a heat pipe [12]. Xu Zhiguo et al. studied the pool boiling heat transfer performance of gradient pore density porous foam and analyzed the factors affecting the thermal conductivity efficiency of gradient pore density foam metal [13]. Li Beibei et al. simulated double diffusion natural convection phenomena in a uniformly filled porous medium cavity using the thermal Lattice–Boltzmann method [14]. Ouyang Li and Liu Wei [15] studied the heat transfer and flow characteristics of porous thermal storage walls in greenhouses, analyzing the relationship between the heat transfer efficiency between the solid skeleton and the air of the porous thermal storage wall, air inlet velocity, porosity and permeability of the porous material, and thermal conductivity of the solid skeleton. Han Jida et al. [16] introduced the concept of minimum gradient to describe the quantitative behavior of capillary water movement lag in porous media, establishing a system theory for heat and mass transfer in unsaturated moist porous media based on capillary hysteresis effect. Yu Boming et al. [17] combined theoretical solutions for transient temperature and humidity distribution in moist porous media with measured temperature and humidity values at certain points in the medium to propose a parameter estimation method for determining thermal-hydraulic migration characteristics of moist porous media. Xiong Jianyin and Zhang Yiping et al. [18] proposed a dual-scale computational model for porous building materials that can couple micro- and macro-pore migration processes of volatile organic compounds (VOCs). Gu Wei et al. [19] used a Maxwell–Stefan model to simulate diffusion process of mixed gases in porous media, providing new research tools for characterizing multi-component gas mixing diffusion in pore scale studies. He Xinting and Wang Moran [20] used the Lattice–Boltzmann method to simulate the diffusion process of gas in the pores of reconstructed porous structures, and analyzed the relationship between the equivalent diffusion coefficient in microporous media and structural characteristics. Wang Huilin et al. [21] established a mathematical model for the thermal-humidity-force bidirectional coupling of heat and mass transfer processes inside moist porous media under convective drying conditions, and studied the heat and mass transfer mechanism as well as the stress–strain distribution rules of biological porous media during hot air drying.

2.2. Study on Shrinkage Deformation in Heat and Mass Transfer of Porous Media

Researchers at home and abroad have conducted extensive experimental research on water transport and shrinkage deformation within deformable porous media. Tsuruta et al. studied the deformation of materials during microwave vacuum drying [22]. Luis A. Segura et al. investigated the relationship between moisture content, capillary pressure, and microstructural changes during heat and moisture transfer in apple slices, and analyzed that the capillary pressure within micro-pores is the main cause of irregular shrinkage deformation [23]. B. Ortiz et al. used digital image processing technology to analyze the shrinkage deformation phenomenon of potato slices during heat and moisture transfer [24]. Yuan Yuejin et al. conducted experimental research on the shrinkage deformation of porous media in hot air drying processes using fruits and vegetables as objects, and analyzed the mechanism of shrinkage deformation during heat and mass transfer [25]. The experimental results showed that during material handling and drying processes, the deformable porous skeleton undergoes deformation or even continuous movement under external forces, and changes in the solid-phase skeleton structure will inevitably affect the internal fluid transport process.

In order to further explore the bi-directional coupling relationship between water transport and deformation in the heat and mass transfer process of deformable porous media, Yuan Yuejin et al. constructed a pore network model and a mathematical model of heat and mass transfer and stress–strain at the micro-pore scale to study the coupling mechanism of water transport and shrinkage deformation [26]. Mohammadreza et al. used a thermal-hygro-mechanical coupling model to study heat and mass transfer in soil under transient and quasi-steady-state conditions, showing that pore structure and thermal parameters have significant effects on fluid flow [27]. Ben et al. established a thermal-hygro-mechanical coupling model based on Terzaghi's effective stress theory to study the drying kinetics and energy-saving effects of deformable porous media under different working conditions [28]. Wang Huilin et al. studied the heat and mass transfer mechanism of biological porous media during hot air drying, as well as the distribution law of internal stress–strain, establishing a mathematical model for bi-directional coupling of heat-humidity stress in the heat and mass transfer process of moist porous media under convective drying conditions [21]. The analysis results showed that irregular shrinkage deformation caused by thermal stress and humidity stress generated by temperature gradient and humidity gradient during heat and moisture transfer process in porous media greatly reduces the quality of dried materials. In order to improve this irregular deformation, an external force field needs to be introduced.

3. Research on Microwave Enhanced Heat and Mass Transfer in Porous Media

In terms of mass transfer enhancement in porous media, the application of the microwave-enhanced drying of porous materials is the main area both domestically and internationally. A large amount of research has been conducted on the characteristics of combined hot air–microwave drying, drying kinetics, and optimal drying processes.

Jianfang Yu et al. systematically studied the variation and distribution of moisture content, temperature, and water vapor pressure inside wood during microwave drying process, and analyzed the influence of microwave action on heat and mass transfer laws in wood [29]. Zhan Yong Li et al. experimented with vegetables as the research object to study the effects of shape and size, cavity size, waveguide position, and material type on material temperature distribution, and analyzed the law of microwave energy absorption [30]. Xukun Zhang et al. conducted experiments on lotus seeds for hot air and microwave temperature control as well as their combined drying, studying the characteristics and kinetics of hot air and microwave temperature-controlled drying of lotus seeds as well as the process for combined hot air–microwave temperature-controlled drying [31]. Cheng Jun et al. have revealed the unique drying and moisture diffusion mechanism of microwave-assisted drying of lignite. They studied the influence of factors such as microwave power, coal particle size, initial quality of coal, initial moisture content of coal, and the height-to-diameter ratio of coal stack on the dehydration kinetics of microwave heating, and proposed to use inorganic ions to improve the dielectric properties of lignite to promote efficient microwave-assisted dehydration [32]. Zhao Jun et al. characterized substrate materials and extracts from micro-nanoscale using scanning electron microscopy, mercury porosimeter, specific surface area analyzer, membrane ultrafiltration, atomic force microscope, and high-performance liquid chromatography. They conducted an in-depth study on the relationship between substrate material microstructure and macroscopic performance, processing technology, and product quality. They also investigated the impact of microwaves on material flow and mass transfer [33]. Binqi Rao et al. attempted to apply microwave fields to pretreat municipal sludge for ultra-high pressure filtration dehydration. The experiment showed that microwave pretreatment was beneficial to sludge dewatering and reduced the moisture content of sludge to 28% after treatment [34,35]. Ayea et al. found through experimental research that microwave–hot air drying increased the drying rate by 37% and reduced the shrinkage deformation rate by 54% compared with hot air drying during the drying process of eggplant, and also improved the rehydration rate [36]. A. Mousa and others studied the effect of microwave radiation on the physical properties and morphological structure of olive shells, and found that microwave heating was faster, more uniform, and easier to penetrate into internal particles [37].

In order to reveal the influence of microwaves on heat transfer in porous media during the transmission process, domestic and foreign researchers have also conducted a lot of theoretical research.

Liang Shan et al. conducted a deep analysis of the absorption mechanism of microwaves on dielectric media, established a thermodynamic model for the microwave drying process of water-containing porous media, designed a temperature optimization control strategy, and effectively ensured the drying quality of lignite [38]. Chen Meiqian et al. revealed the coupling transmission mechanism and physical structure formation and evolution mechanism of multiple loss mechanisms in mineral porous media under microwave fields from two aspects: dielectric loss mechanism and dielectric/magnetic loss mechanism. They also established a dynamic model describing the thermal-hygro coupled transport characteristics inside porous media under microwave field, further revealing the essence of internal transfer processes in mineral porous media under a microwave field [39]. Vineet et al. studied the effect of microwave fields on temperature distribution, moisture distribution, and volume change during the expansion process of deformable porous media based on thermodynamic model [40]. Khomgris Chaiyo developed a two-dimensional model for heat and mass transfer and pressure distribution in an unsaturated porous fluidized bed and studied the effects of vacuum pressure and microwave parameters on fluid movement in porous media during microwave–vacuum drying [41]. Santiphong Klayborworn et al. numerically studied the heating process of a double-layered porous medium under microwave field, and analyzed the influence of material thermodynamic properties and dielectric characteristics on heat transfer [42]. Huacheng Zhu et al. established a thermodynamic model by coupling electromagnetic fields and multiphase porous media transport models to investigate the effects of shape, size, and characteristic parameters of spherical samples on microwave drying process. The accuracy of the model was verified through experiments, and internal temperature, humidity, and pressure distribution within the sample were analyzed [43,44]. Kumar and Karim established a multiphase transport model for the microwave convective drying process, systematically studied temperature distribution, humidity distribution, and pressure distribution in porous media, and found that considering shrinkage deformation and pore evolution in the model was more consistent with the experimental results based on the simulation results [45–47].

In recent years, researchers both domestically and abroad have conducted extensive research on the mass transfer within porous materials enhanced by microwave irradiation, and have achieved many valuable results. It has been found that due to its rapidity, high efficiency, timeliness, and selectivity, microwave irradiation can effectively promote the transfer of internal components. Additionally, the deformation and evolution of physical properties and structural morphology caused by microwave irradiation in porous media also have important effects on component transport.

4. Study on Ultrasonic Enhanced Heat and Mass Transfer in Porous Media

Ultrasound, as a new form of energy, can produce mechanical effects, sponge effects, and cavitation effects when propagating in a medium. During the propagation of ultrasound, due to the mechanical effect, the medium particles will alternate between compression and extension, forming pressure changes inside the medium and generating large particle accelerations. In the process of cavitation, when cavitation bubbles collapse instantaneously, they release concentrated sound field energy in a very short time and small space, forming a high temperature above 5000 K and a high-pressure environment of 5×107 Pa while producing significant impact force and generating a large number of microbubbles [48]. Based on these effects, ultrasound has been developed and applied to different degrees in extraction, sterilization, drying, filtration, and cleaning. The ultrasound field can enhance the heat and moisture transfer process in porous media and have shown important application prospects in areas such as wastewater treatment, food drying, dehumidification regeneration, solid waste treatment, and the development of new acoustically active materials, which have attracted widespread attention from the scientific and engineering communities at home and abroad.

4.1. Study on Ultrasound Enhancement of Moisture Transport in Porous Media

In terms of mass transfer enhancement in porous media, both domestic and foreign research mainly focus on the application of ultrasonic-enhanced drying of porous materials. Experimental studies have demonstrated that ultrasonic waves are an effective technique to enhance mass transfer in porous media. Moy and DiMarco [49] applied ultrasound as a form of energy to freeze-drying systems and conducted experimental research. Nomura Murakami [50] studied the effect of ultrasonic vibration on natural convection heat transfer, and found that when the distance between the ultrasonic transducer and the heat transfer surface was 15 mm, the enhancement of natural convection heat transfer by cavitation reached up to three times, and the best enhancement effect was achieved when the ultrasonic transducer was located below the heat transfer surface. Santacatalina et al. [51] applied ultrasound-assisted technology to freeze-drying carrots, and found that under the same conditions, the drying rate could be increased by 73%. Fuente-Blanco et al. [52] conducted experimental research on the ultrasonic drying of cylindrical carrots, using a high-power rectangular aluminum plate transducer in their experimental system. The results showed that ultrasound power had a significant impact on the carrot dehydration process, and higher ultrasound power led to higher dehydration rates for samples within the same time frame. García-Pérez and colleagues [53–55] conducted a series of experiments and theoretical studies on ultrasound-assisted convective drying processes for food. The results showed that increasing the ultrasound power, drying air velocity, and temperature can accelerate the drying process. Ultrasound had a more significant effect on materials with high porosity, and a theoretical model was developed to fit the relationship between different parameters (ultrasound power, air velocity, temperature) and the mass transfer coefficient and heat transfer coefficient during the drying process. Cárcel et al. [56–58] studied the effects of high-intensity ultrasound on pork marination and apple mass transfer in sugar solutions through experimental research. Three treatment methods were compared: static (STAT), agitation (AG), and ultrasound. The results showed that different intensities of ultrasound have varying effects on mass transfer processes, and only when the ultrasound intensity reaches a specific value can mass transfer be enhanced. Subsequently, they also studied the drying process of carrots and found that as the sample's quality load density increases, the promoting effect of ultrasound on drying rate is weakened. Schössler et al. [59] combined ultrasonic transducers with a drying sieve and successfully applied it to the drying process of foods such as apples and red peppers, significantly improving the drying rate. They compared the effects of continuous and intermittent ultrasound on the results, indicating that as the net ultrasound action time shortened, the improvement effect on the drying rate weakened, but showed a nonlinear relationship. Tao and Sun [60] systematically summarized the current application status of ultrasonic waves in the food industry and pointed out the main influencing factors and future development directions of ultrasonic-assisted intensified food drying processes. Feng et al. [61,62] conducted experimental studies on the dewatering performance of activated sludge under ultrasonic action. The results showed that when the ultrasonic energy consumption was 800 kJ/kgTS, the sludge achieved optimal dewatering performance, with EPS concentrations ranging from 400 to 500 mg/L and floc particle diameter distributions ranging from 80 to 90 μm, while when the ultrasonic energy consumption exceeded 4400 kJ/kgTS, the dewatering performance of sludge was severely deteriorated. Chen et al. [63] studied the drying process of cake-like sludge materials, analyzed the changes in material pore structure caused by cracks formed due to shrinkage during the drying process, and the influence of pore structure on the moisture migration mechanism inside the sludge. Zhao Fang et al. [64,65] studied the drying process of sludge and food under ultrasonic assistance, and found that ultrasonic treatment effectively accelerated the moisture migration rate of sludge in their preliminary study. Moreover, they pointed out that the higher the sound energy density, the more obvious the enhancing effect of ultrasonic waves on sludge drying. Kim et al. [66] investigated the application effects of emulsification technology, ultrasound, and microwave radiation in sludge drying and dehydration processes. They compared and analyzed their dehydration abilities and energy consumption, and pointed out some problems with ultrasonic technology in sludge dewatering applications. Tyagi et al. [67] summarized various applications of ultrasound in sludge dissolution, harmful pollutant degradation, chemical substance extraction, etc., elaborating on various mechanisms of ultrasound's action on sludge treatment, and pointed out future development directions for ultrasound-based sludge treatment technologies. Chen Zhenqian et al. [68–71] built an experimental platform for ultrasound-assisted hot air drying, and conducted a series of comparative experiments on typical deformable porous media such as municipal sludge, porous fibers, and activated alumina particles; the schematic diagram of the experimental system is shown in Figure 2. The drying kinetics under different operating conditions were studied, and the process parameters of the ultrasound-assisted drying system were optimized through response surface methodology and artificial neural network models.

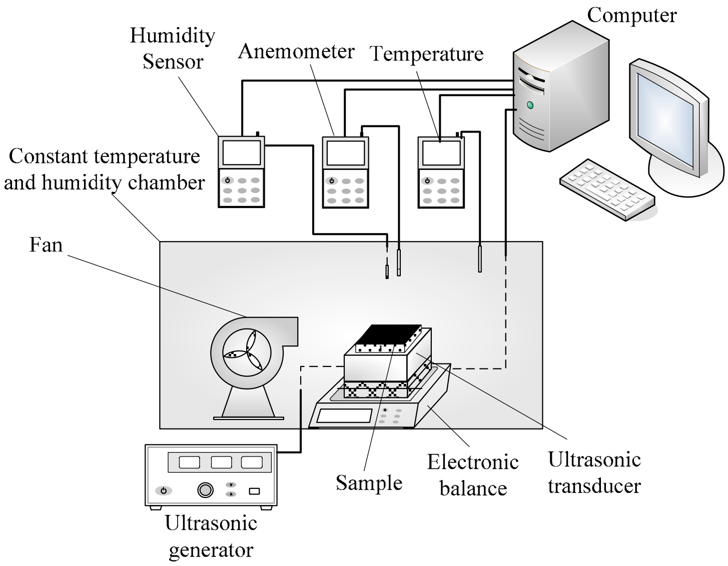


Figure 2. System diagram for ultrasound-assisted air drying of porous media.

For porous fiber adopted in experiments, as the ultrasound power increases, the moisture diffusion coefficient increases. When the ultrasound frequency is 20 KHz and the power is 500 w, the drying time decreases by 13% and, relatively, saves energy.

The above research mainly studied the enhancement effect and influencing factors of ultrasound on mass transfer efficiency through experimental methods, and preliminarily explained the reason for the enhancement of mass transfer efficiency by ultrasound. In order to quantitatively analyze the effect of ultrasound on mass transfer efficiency in porous media, some theoretical models have also been proposed to describe the heat and moisture migration process inside porous media.

Santacatalina et al. [72] established a drying kinetics model for apple enhanced by ultrasound, assuming that the process was determined solely by diffusion (D model) when external resistance was not considered, and was jointly determined by convection and diffusion (D+C model) when external resistance was considered. The fitting of experimental results to the theoretical model showed that considering external resistance was more appropriate. Jose et al. [73] fitted the experimental results of the ultrasonic-assisted drying of fruits and vegetables to the theoretical model, showing that the D+C model had better fitting results, and the enhancement effect of ultrasound was mainly achieved through influencing external resistance. Ye Yao et al. [74,75] fitted the experimental results of the ultrasound-assisted silica gel desiccant regeneration process to different theoretical models, and the schematic diagram of the experimental system is shown in Figure 3. The results showed that Gaussian and Weibull's proposed theoretical models were more suitable for this drying process. Subsequently, a theoretical model coupling acoustic field with heat and moisture transfer processes was established to simulate the dehydration regeneration process of ultrasonic-assisted silica gel desiccant, and the accuracy of this theoretical model was verified through experiments. Equations relevant to the heat and mass transfer of a silica gel-packed bed during the regeneration process can be summarized as below:

$$(1-\varepsilon)\rho_s C_s \frac{\partial t_s}{\partial \tau} = H_m S_b (t_a - t_s) - H_{ads} K_m S_b (w_s^* - w_a) + \frac{a_c \eta_T I_0}{(1-\varepsilon)V} \quad (1)$$

$$-(1-\varepsilon)\rho_s \frac{\partial q_s}{\partial \tau} = K_m S_b (w_s^* - w_a) \quad (2)$$

$$\rho_a C_{p,a} u_a(x) \frac{\partial t_a}{\partial x} = H_m S_b (t_s - t_a) + K_m S_b c_{p,v} (w_s^* - w_a)(t_s - t_a) \quad (3)$$

$$\rho_a u_a(x)\left(-\frac{\partial w_a}{\partial x}\right) = (1-\varepsilon)\rho_s \frac{\partial q_s}{\partial \tau} \tag{4}$$

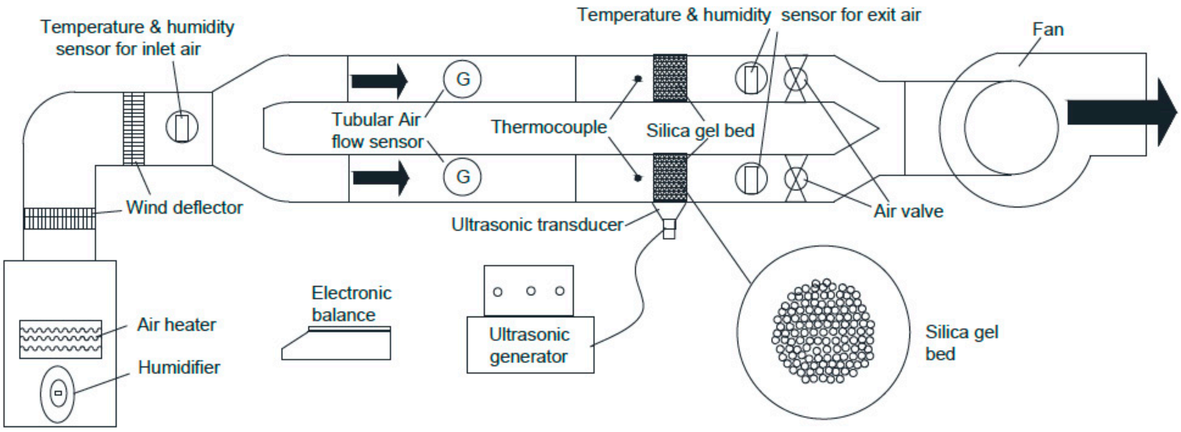


Figure 3. Schematic diagram of solid desiccant regeneration test system based on ultrasound.

Equations (1)–(4) correspond to the energy and moisture conservation of the solid and gas media in the bed, respectively.

Chen Zhenqian et al. [76,77] established a mathematical model for thermo-hydro-mechanical coupling in deformable porous media under ultrasound at the macroscopic scale, further revealing the strengthening mechanism under ultrasound. The wave equation based on the Biot theory is expressed by basing the displacement u and pressure change pf in porous media:

$$-\omega^2\left(\rho_{av} - \frac{\rho_f^2}{\rho_c(\omega)}\right)\mathbf{u} - \nabla\left(\sigma_d(\mathbf{u}) - \alpha_B p_f \mathbf{I}\right) = \frac{\rho_f}{\rho_c(\omega)}\nabla p_f \tag{5}$$

$$-\frac{\omega^2}{M}p_f + \nabla\left[-\frac{1}{\rho_c(\omega)}\left(\nabla p_f - \omega^2\rho_f\mathbf{u}\right)\right] = \omega^2\alpha_B\varepsilon \tag{6}$$

The frequency of ultrasound mainly affects the distribution trend of displacement, while the intensity significantly affects the sound pressure and displacement size in porous media, and the pressure value and displacement size are approximately proportional to the intensity.

The model for heat and mass transfer in fibrous porous media can be described as follows:

$$\frac{\partial X}{\partial t} + \nabla(Xu_l) = D_{eff,l}\nabla^2 X + \delta_{m,l}D_{eff,l}\nabla^2 T \tag{7}$$

$$u_l = -\frac{K_l}{\mu}(\nabla p_u - \rho_l g) \tag{8}$$

$$(\rho c)_{eff}\frac{\partial T}{\partial t} + \varepsilon\rho_l C_{pl}\nabla(Tu_l) = \lambda_{eff}\nabla^2 T + C_{pl}\xi_{q,l}D_{eff,l}\nabla^2 X + q_m \tag{9}$$

The numerical simulation results showed that the presence of ultrasound increases the temperature gradient inside the porous media, and the transfer rate of moisture increases in an ordered direction. Alternating expansion and compression made the macroscopic deformation of porous media smaller.

Ma Qiang et al. [78,79] used the immersed boundary lattice Boltzmann method to study in depth the heat and mass transfer process in deformable porous media on the pore scale, elucidating the coupling relationship between heat and mass transfer processes and the deformation of porous skeleton.

4.2. The Analysis of Ultrasound-Enhanced Mass Transfer Mechanisms in Porous Media

Many studies have been conducted on the effect of ultrasound on pore structure in porous media. Fernandes et al. [80–82] conducted a series of studies on ultrasound-assisted drying processes for tropical fruits such as watermelon and papaya. The study showed that when dehydration was less than 30 min, the diffusion rate of water decreased due to sugar condensation. After one hour, the diffusion rate of water increased due to cell damage and increased diffusion resistance. Ultrasound pretreatment can form microchannels in tissues, thereby increasing the diffusion rate of water. Hottot et al. [83] studied the freeze-drying process of mannitol and found that after applying ultrasound to the process, nucleation sites can be increased without affecting the original sample structure and crystallinity, thus accelerating the drying process and avoiding annealing treatment after freezing. He et al. [84] pre-treated poplar wood and found that the mechanical effect caused by ultrasound can form new microchannels in the internal structure of wood, which is conducive to water transfer, accelerates the drying process, and with increasing ultrasound power and prolonged action time, poplar wood has a higher drying rate. Chu et al. [85] conducted experimental research on the physical, chemical, and biological properties of activated sludge under the action of ultrasound with a frequency of 20 kHz and different sound powers. The study showed that when the ultrasonic sound energy density was greater than 0.22 W/mL, the floc particle size decreased significantly. After 20 min of ultrasonic treatment at a sound energy density of 0.44 W/mL, the floc particle diameter decreased to less than 3 μm. A further extension of time did not result in significant changes in particle size. Jiang et al. [86] studied the dehydration effect of ultrasound during Fenton oxidation treatment of sludge, and demonstrated, through comparative experiments, that when Fenton oxidation and ultrasound were applied simultaneously, the oxidant consumption and reaction time were both significantly reduced. Moreover, the microstructure of sludge treated with ultrasound appeared finer and looser. Chen Zhenqian et al. [69,87] constructed a visualization experimental platform to study the variation law of pore structure in deformable porous media under ultrasonic pretreatment (the experiment schematic is shown in Figure 4) and then analyzed the topological characteristics evolution law of pore structure using fractal theory, and explored the influence of ultrasound on mass transfer characteristics in deformable porous media. The results showed that, as shown in Figure 5, ultrasound can increase the pore area of porous media and the wet diffusion coefficient increases gradually with increasing ultrasonic power.

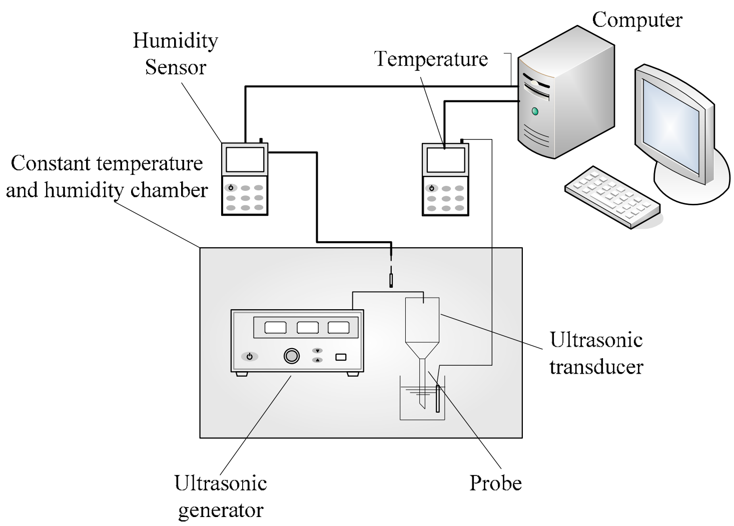


Figure 4. Schematic of the experimental set-up of the ultrasound pretreatment system.

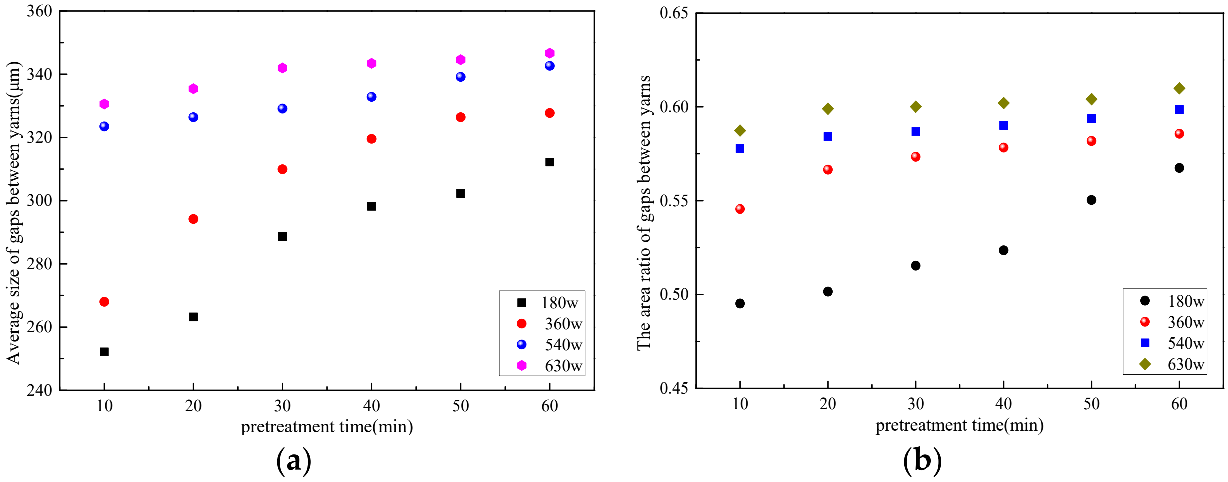


Figure 5. (**a**) The average pore size under different ultrasound pretreatment power and treatment time; (**b**) the porosity in the surface under different ultrasound pretreatment power and treatment time.

The sponge effect is one of the reasons for the enhanced heat and mass transfer by ultrasound. Gallego-Juárez et al. [88] compared ultrasound-assisted hot air drying with traditional drying methods for vegetables and found that ultrasound can increase the drying rate, reduce the final moisture content, and better preserve the original quality of the vegetables. Direct contact between ultrasound and materials was also more effective than indirect contact. They proposed that ultrasound can accelerate drying because, under high-intensity ultrasound, materials produce a sponge effect that leads to a series of rapid compression and expansion, thereby increasing the transport speed of water in both the original channels of tissue structure and new channels formed under ultrasound. Zhao Fang et al. [89,90] conducted experimental studies on the ultrasonic pre-drying treatment of apple slices and carrot slices, and found that ultrasound can effectively enhance the drying process. The influence of ultrasound on the internal moisture diffusion coefficient of samples gradually increased with increasing ultrasonic intensity. In addition to cavitation effects, this phenomenon should also be attributed to the repeated compression and stretching of a material's internal structure by ultrasound, resulting in a sponge effect. This structure reduced the surface adhesion force of water, facilitating water migration. Garcia et al. [91] studied the experimental process of the ultrasound-assisted drying of orange peel. The study showed that due to the sponge effect of ultrasound, the degradation of reflectivity in orange peel tissue was more significant compared with when ultrasound was not applied, which led to an acceleration in the water transfer rate and greatly shortened the drying time. Mulet et al. [92] summarized the effect of ultrasound on solid–liquid and solid–gas mass transfer processes from the perspective of internal and external mass transfer resistances. The sponge effect was an important mechanism that cannot be ignored for ultrasound to promote mass transfer processes.

The cavitation effect is another main reason for the enhanced heat and mass transfer by ultrasound. Mason et al. [93] discussed the application of ultrasound in food technology. The mechanical and chemical effects of cavitation result in low-frequency ultrasound being widely used for sterilization, extraction, freezing, filtration, emulsification, etc., effectively reducing processing time and improving efficiency. Sun et al. [94,95] studied the heat and moisture transfer mechanism during food freezing using power ultrasound, considering the effects of different factors such as ultrasonic power, operation time, and sample structure on freezing rate. The study showed that the cavitation effect of ultrasound can promote nucleation and ice crystal growth while generating microfluidic flow to enhance heat and moisture transfer, thus effectively improving freezing rate and preventing cell damage and loss of nutrients. Soria et al. [96] summarized the role and mechanism of ultrasound in the field of food drying, pointing out that cavitation effect in the liquid phase is the main mechanism for ultrasound to promote the mass transfer process. Teihm et al. [97,98]

found that when the frequency of ultrasonic action was low, larger cavitation bubbles were generated in sludge, which would collapse and produce strong shear force. The short-term treatment of sludge could destroy the structure of sludge flocculent without damaging cells. However, long-term treatment would destroy microbial cell walls and release organic matter, thereby improving the anaerobic digestion performance of sludge. When the frequency of ultrasonic action was high, the radius of cavitation bubbles decreased and the cavitation effect weakened, resulting in less significant effects on sludge by ultrasonic treatment.

From the current research status, it can be seen that, in recent years, domestic and foreign researchers have conducted a lot of research on the mass transfer of porous media enhanced by ultrasound. They have achieved many valuable results and found that ultrasound can promote the evolution of pore structures and form micro-pore channels during the drying pretreatment stage of porous media, which promotes internal component transfer. During mass transfer, the sponge effect and cavitation effect formed by the mechanical and acoustic effects of ultrasound also have important influences on component transport.

5. Conclusions

The heat and mass transfer process of deformable porous media includes the transfer of energy, mass, and momentum inside the porous media and the exchange of heat and mass between the material surface and the external environment. Through the research of many scholars at home and abroad in recent years, we can draw the following conclusions:

(1) Convective drying of deformable porous media is accompanied by complex heat-moisture-force transfer processes. The thermal and mass transfer during the drying process leads to the deformation and shrinkage of the porous media due to the reduction in moisture content. This physical deformation partially restricts the heat and mass transfer processes. In addition, deformation-induced shrinkage, surface hardening, etc., can damage the quality of materials and greatly reduce the quality of dried materials. To improve this irregular deformation, an external force field needs to be introduced.

(2) Microwave heating has high efficiency and low energy consumption due to its directionality of and mass transfer, which is beneficial for strengthening the heat and transfer processes of deformable porous media. At the same time, due to the timely and uniform control of microwave heating, it may have some improvement on irregular deformation during the heat and moisture transfer process of deformable porous media. As moisture decreases inside the medium during microwave drying, dielectric loss value decreases and microwave energy utilization decreases.

(3) The research on the enhancement mechanism of ultrasound on the thermal and moisture transfer process in deformable porous media has important guiding significance for the development of the reinforcement technology, which has been investigated by experiment and theory methods. First, a visualized experimental platform was established to study the laws of the pore structure of the porous media under the action of ultrasound pretreatment and the evolution of the topology characteristics of the pore structure was analyzed by using the fractal theory. The results show that, ultrasound can increase the pore area of the porosity medium, and the effective diffusion coefficient of the wet division gradually increases with the ultrasonic power. Then, a macro-scale ultrasonic-heat-wet-force mathematical model was established, which further revealed the enhanced mechanism under the action of ultrasound. The numerical simulation results indicate that the presence of ultrasound increases the internal temperature gradient of the porous medium. The wet division transmission rate increases and the direction is orderly. The alternate expansion compression makes the macro variation of the porous medium smaller. After that, an ultrasound assisted hot air drying experimental platform was established, which conducted a series of comparison experiments for typical deformable porous media such as municipal sludge, porous fibers, and active aluminum particles. The process parameters of the ultrasonic auxiliary drying system are optimized through the response facial method

and artificial neural network model. However, due to the complexity of the pore structures inside porous media, especially when characteristic dimensions are often in the micro-nano scale range, macroscopic theories cannot accurately describe heat and mass transfer processes. Therefore, under ultrasound, the coupling relationship between heat and moisture migration processes and non-steady shrinkage deformation still requires further microscopic analysis at this time.

Author Contributions: Acquisition of data: P.L., H.W., Y.W. and H.B.; Analysis of data: P.L. and C.M.; Drafting of the manuscript: P.L.; Critical revision of the manuscript: Z.C. and P.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 51676037.

Data Availability Statement: All relevant data are within the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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