Abstract: Drying is an extremely energy-intensive process. Superheated steam as a drying medium can improve the energy efficiency of the drying processes. In superheated steam drying, waste heat can be recovered by condensing the exhaust steam or raising its specific enthalpy. Spray drying is widely used in industry, even though its energy efficiency is often low. Substitution of air by superheated steam as a drying medium in a spray dryer may reduce the energy consumption of the drying process by 20–30%; moreover, if excess steam generated by moisture evaporation is upgraded to a higher temperature level and reused for drying, the energy demand could be decreased by even 80%. A literature review showed that superheated steam spray drying was successfully applied for both thermally resistant and a wide range of thermally sensitive materials. Superheated steam drying gives a number of advantages in terms of product properties, i.e., higher particle porosity due to rapid moisture evaporation results in improved powder rehydration properties. Additionally, steam drying may be applied for in situ particle crystallization. Taking into account the advantages of superheated steam drying and the potential application of this technology in spray drying systems, there is a great need for further research in this field. This literature review aimed to present an energy-saving solution, i.e., superheated steam spray drying process, showing its advantages and potential applications, followed by drying kinetics, providing analysis of the research papers on experimental studies as well as mathematical modeling of this drying technique.

Keywords: superheated steam; spray drying; energy efficiency; particle morphology; mathematical model

1. Introduction

The spray drying process consumes a vast amount of energy in the production of powders such as pharmaceuticals, foods, blood plasma, different organic and inorganic chemicals, rubber latex, ceramic powders, detergents [1]. In spray drying, small drops of the solution/suspension come into contact with hot air. The drying time is very short, which reduces the thermal degradation of the product [2]. Additionally, the spray drying process offers the possibility to control the final product properties such as particle size distributions, moisture content and bulk density [1]; spray drying allows continuous high-capacity production of homogeneous particles with perfectly mixed ingredients, e.g., in detergent drying [3–5].

In the literature, a large number of research papers on spray drying technology with the application of air as a drying medium can be found. For specific information about the spray drying process, the reader is referred to the one of review papers which emerged in recent years. Typical spray dryer configurations, a brief background on spray atomization and particle separation equipment are presented in the work of Bellinghausen, 2019 [3]. The theoretical background and principles of mathematical simulation of the spray drying process is described in detail in the review of Oakley, 2007 [6] and Razmi et al., 2021 [7].
Zbicinski, 2017 discussed the recent findings in industrial spray drying covering both experimental research and simulations [8]. A comprehensive review by Samborska et al., 2022 is focused on the drawbacks of conventional spray drying technology and discusses emerging modifications of spray drying systems with attention to an energy reduction of the process, improvement of process flow and final product properties [9].

Spray drying in air has some limitations, for instance: low thermal efficiency; high volumetric flow rate of air [1]; high production rate requires an increase in the dryer size leading to high investment costs; risk of dust explosion and fire hazard; oxidation hazard; risk of air pollution since used drying air is discharged into the atmosphere.

The use of superheated steam (SHS) as a drying medium instead of air can, in some cases, help to overcome these problems.

2. Superheated Steam Drying

2.1. Advantages of Superheated Steam Drying

In the conventional hot-air drying process, the exhaust drying air is discharged into the atmosphere; therefore, the recovery of waste heat after drying is limited. According to Mujumdar, 2006 [10] one of the major advantages of SHS drying is the possibility to recover waste heat after SHS drying by condensing the exhaust steam or elevate exhaust steam specific enthalpy for reuse in the dryer (for example, by compression or applying heat pumps). In SHS drying, the latent heat supplied for evaporation might be recovered by condensation, and up to 85% of input energy might be saved [11].

In cases of drying systems integrated with energy management in a large plant, the energy input of evaporating 1 kg of moisture can drop to as low as 1000–1500 kJ/kg. In the corresponding hot-air drying process, energy consumption is in the range of 4000–6000 kJ/kg water removed [10]. Thus, the reduction in energy consumption is an obvious advantage of SHS drying.

In addition, SHS drying provides environmental benefits by eliminating emissions of odors, dust, or other hazardous components from the drying process by condensation of the exhaust steam. During condensation, pollutants are transformed into liquid form and then may be easily separated [12].

SHS drying gives the advantage of the improvement of process safety and final product quality. Unlike hot-air drying, in SHS the oxygen is absent, and the risk of fire hazard and explosion is minimized [12].

Due to the same reason, the deterioration of biological materials via oxidation during SHS drying is hampered if drying is carried out at an appropriate temperature.

In SHS drying, such processing steps as blanching, sterilization, pasteurization [12] and deodorization of the product may be performed in one-unit operation, i.e., during drying [13], thereby energy-intensive and expensive pre-/post-processing of the product can be avoided.

The enhancement of dried product structure and morphology after SHS drying has been reported by several authors. Erkinbaev et al., 2019 reported an increase in volumetric expansion of the distillers’ spent grain pellet in the range of 90–133% as well as an increase in open porosity after SHS drying, which reduced drying time by ca. 81% compared to conventional hot-air drying [14]. Similar observations were reported by Brar et al., 2021 during a comparative study of SHS and hot-air drying of yellow pea (Pisum sativum L.), i.e., the porosity of yellow pea increased from 19.1% to 35.0% in SHS drying [15]. Moreover, Bao and Zhou, 2017 showed that an increase in porosity and greater wall cell damage of Chinese cedar wood led to an increase in drying rate in SHS drying when compared to hot-air drying [16]. In a study by Liu et al., 2017 an increase in the porosity of white radish during SHS drying was favorable since it improved the rehydration capability of dry product [17].
2.2. Application of Superheated Steam Drying

SHS drying has been applied in different dryer types (flash, fluidizing bed, impinging jets dryers, conveyor dryers, agitating and packed bed dryers) to evaporate moisture from different types of products such as sludges, coal, beet pulp, lumber, peat, paper and tissue and wood [18]. Alfy et al., 2016 in their comprehensive review on SHS drying of food products reported the successful application of SHS drying solely or in combination with other drying techniques for meat and fish products (zousoon, chicken meat, fish press cake), fruits (banana slices, mangosteen rind, longan, Indian gooseberry), vegetables (carrot, potato), milk products (cottage cheese), cereals and beans (spent grains, paddy, soybean) as well as spices and herbs (coriander and pepper seeds, basil leaves) [19].

The literature review on the application of SHS steam drying for fundamental and basic research as well as for applied research has been published by Li et al., 2016 [20]. The paper discusses design aspects, energetic performances and mathematical modeling of SHS dryers for oven dryers, tunnel dryers, and fixed bed dryers on a laboratory scale for fundamental research. An extensive overview of SHS drying in the industrial and pilot scale dryers has been also carried out in the review [20] for:

- Kiln dryers—wood drying
- Rotary drum dryers—lignite, fish press cake and brewer’s spent grain drying
- Fluidized bed dryers—parboiled rice, Thai native rice cultivars, sawdust, paddy and seeds, pulp and biomass
- Flash dryers—fishmeal drying
- Impingement dryers—fish press-cake and seeds drying.

A few examples of the application and theoretical analysis of SHS drying in industrial-scale dryers are discussed below.

An example of the successful application of SHS drying is the dryer developed by Jensen, 2015 [21]. So far, several dozen of such dryers for drying sugar beet pulp have been put into operation. A beet pulp with about 28% dry mass is a waste product of the sugar extraction process, which is produced in the amount of 100 t/h in the average size sugar factory. Dried beet pulp may be applied as a high-value cattle feed or as an energy source used for the operation of the sugar factory. The application of fluidized bed pressure steam dryer for beet pulp drying instead of a conventional hot-air drum dryer allows for significant energy savings. Thus, an industrial-scale dryer with a capacity of 71 t/h of water evaporation (Nampa, ID, USA) saves 200 t/day of coal and reduces CO$_2$ emission by about 600 t/day [21].

Chryat et al., 2019 reported an application of an SHS co-current triple pass rotary dryer for beet pulp dewatering on an industrial scale with an evaporation capacity of up to 100 kg/h [22]. To separate the dried product from the SHS a cyclone separator with a rotary SHS lock valve and deflectors has been applied. To clean the exhaust vapor and to transfer SHS to a saturated state the wet scrubber has been applied. After steam condensation, the remaining noncondensable gases (e.g., air, volatile organic compounds) were separated and burned off. The operation of the dryer at an overpressure of 1 to 2 bars allowed for avoiding air leakage into the dryer and provide an enhanced energy recovery of the removed vapor. Experimental tests on beet pulp drying (27% dry matter) were carried out at inlet SHS temperatures of 260 °C to 297 °C and a pressure of 1.09 and 1.24 bar abs. showed the specific energy consumption per 1 kg of water for the dryer of 3407 kJ/kg and 3398 kJ/kg, respectively.

Jaszczur et al., 2020 carried out a theoretical analysis of the integrated gasification combined cycle coupled with coal SHS drying applied to improve the thermal efficiency of the lignite-fired power plants [23]. The numerical calculations showed that the introduction of the SHS drying system to reduce the moisture content of lignite and to raise its caloric value increases the thermal efficiency of the combined gasification system by up to 47.4–56.4%. An increase in thermal efficiency of power plant operation on lignite combustion permits us to reduce the consumption of coal, and as a result, decrease air pollution and CO$_2$ emission.
The mathematical modeling of SHS drying of bagasse at the sugar factory, where bagasse is applied as a fuel for electrical power generation was carried out by Chantasiriwan and Charoenvai, 2019 [24]. The research group reported a reduction in dry bagasse consumption by 1.2–4.8% and an increase in the energy utilization factor by 1.4–5.3% for system output 6–13 MW when SHS drying is applied to remove moisture from the bagasse prior its supply to the boiler.

The application of SHS as a drying agent in different types of dryers has been thoroughly investigated on a laboratory, pilot, and industrial scale. Nevertheless, the experience on the application of SHS for drying in dispersed systems, i.e., spray dryers is still limited.

3. Theoretical Background of Superheated Steam Drying

3.1. Drying Kinetics of Superheated Steam Drying

The drying kinetics during SHS drying significantly differs from the hot-air drying process. There are three stages in the standard drying process: initial heating of the material, constant drying rate stage and falling drying rate stage. During the initial heating stage, the material is heated up from the initial temperature to the wet bulb temperature. In the first drying stage or constant drying rate period, non-bounded moisture is evaporated from the material and the moisture content of the material is decreasing from initial moisture content to critical moisture content. At the second drying stage or falling drying rate period bounded moisture is removed from the material until the product moisture content reaches equilibrium moisture content (Figure 1a).

![Figure 1](image.png)

**Figure 1.** Drying stages: (a) hot-air drying (green dotted line); (b) SHS drying (blue dotted line) (Based on [25]).

In SHS drying the same three drying stages might be distinguished. However, during the initial stage of SHS drying, condensation takes place at the surface of the material due to a low initial temperature of the material introduced to the dryer. In the next stage, condensed moisture starts to evaporate into the SHS. This initial drying stage combining water condensation and further evaporation from the material during SHS is also known as the reverse process (Figure 1b) which is a unique feature of SHS drying [26]. It was found that moisture condensation in the initial stage of SHS drying may have a favorable effect, for example, higher product yield during rice drying caused by starch gelatinization [19].
During the constant drying rate period, material temperature is constant and equal to saturation temperature. According to Inoue et al., 2010 [27], Pakowski and Adamski, 2011 [28] the critical moisture content in SHS drying is lower compared with standard hot-air drying due to the significantly higher temperature of the constant drying rate period [25]. In the falling rate drying period, the moisture evaporation rate is decreasing, and the material temperature starts to raise in both SHS and the hot-air drying process.

3.2. Inversion Temperature

At low temperatures, the evaporation rate during air drying is always higher than during SHS drying due to higher temperature differences between drying medium and material surface temperature, because in air drying material surface temperature is equal to wet bulb temperature and in SHS drying—to saturation temperature [25]. The first experimental studies on SHS drying, humid air, and dry air drying showed that at a certain temperature, the evaporation rate became independent of the drying medium composition (water vapor content) [29]. In the literature, this temperature is named inversion temperature or inversion point. Below this point, the evaporation rate in SHS is lower compared to air or humid air applied as a drying medium, above the inversion temperature, the evaporation rate in SHS is higher compared with hot-air drying due to transport and thermal property differences between air and SHS (Figure 2). Since 1970, several papers have appeared, where the inversion temperature has been determined experimentally and theoretically. Yoshida and Hyodo, 1970 have been carried out an experiment in a wetted wall column for turbulent flow and determined inversion temperature in the range from 160 °C to 176 °C [29].

Schwertze and Bröcker, 2002 elaborated a theoretical model based on the coupled heat and mass transport equations introducing the concept of local and apparent inversion temperature [30]. For local inversion temperature, an assumption of constant gas parameters in the direction of gas flow is justified in the case of evaporation from the infinitely small material surface. For experimental conditions, the assumption of constant gas parameters in the direction of gas flow could not be applied, therefore the apparent inversion temperature should be calculated. Schwarte and Bröcker, 2002 reported a local inversion temperature of 388.4 °C for constant volumetric gas flow and an apparent inversion temperature between 198.6 °C and 159.3 °C.
3.3. Maximum Drying Rate as a Function of SHS Pressure

Elustondo et al., 2002 have determined a linear relationship between maximum drying rate and SHS pressure [31]. It has been proved theoretically and experimentally that the drying rate with SHS depends on the steam temperature, recycle velocity and SHS pressure. For a fixed steam temperature and recycle velocity, the drying rate may reach a maximum value at an optimal SHS pressure. The authors carried out experiments to determine the relationships between drying rates and SHS pressures at different steam inlet temperatures. The maximum drying rates determined by applying linear Equation (1) have been fitted by the straight line. Equation (1) shows that the maximum drying rate is proportional to the inlet sectional area, \( S_i \), the inlet SHS velocity, \( v_i \), and optimal SHS pressure, \( P_{op} \), and \( K \) is the proportion factor, which might be calculated by applying Equation (2).

\[
m_{\text{max}} = K \cdot S_i \cdot v_i \cdot P_{op}, \tag{1}
\]

\[
K = \frac{C_{PS}}{(\Delta H)^2} \left( \frac{T_{eq}}{T_i} \right)^2 \frac{1 - e^{-Nq}}{1 - R_{Nq}(1 - \varphi N)}. \tag{2}
\]

4. Modeling of Superheated Steam Spray Drying

4.1. Modeling of Isolated Solid Particles Drying in SHS

Mathematical modeling of single droplet/particle drying in SHS has been elaborated for wet solid particles mostly. The papers presented in this section give general information about the modeling of individual wet particles drying in the superheated steam; however, they do not cover the single droplet drying in SHS. Nevertheless, approaches that could be used to elaborate the model of droplet drying in SHS, especially in the second drying stage, are provided.

A mathematical model of solid porous particle drying in SHS taking into consideration four stages: initial particles heating and increase in particle moisture content via steam condensation; water diffusion through particle from surface to the interior due to steam condensation; constant drying rate period; and falling drying rate period, has been developed by Hamawand et al., 2013 [32]. The developed model of solid particles drying has not been verified experimentally.

Kiriyama et al., 2013 elaborated a mathematical model of single lignite particle drying in the SHS [33]. The model considers the wet particle as a distributed system, where variables such as particle temperature and moisture content are functions of time and particle radius. The model includes initial steam condensation on the particle surface, constant drying rate stage as well as falling drying rate stage. To account for the transfer of free water through the porous structure of lignite the authors applied the diffusion coefficient of free water determined experimentally. In the falling drying rate period, to account for additional heat input needed to remove bound water, the enthalpy change of bound water evaporation was calculated from approximated expression. The results of the mathematical simulation were in agreement with the experimental results of lignite particle drying with a diameter of 30 mm. In a further study, the mathematical model was modified and applied to smaller particles, the authors claimed that the presented model may be applied for SHS drying of lignite particles in the size range from a few millimeters to several centimeters [34]. In the next work, the single-particle model was extended to multiple particle drying [35].

In recent contributions from Tsotsas and co-workers, SHS drying of single wood and rice particles was studied and modelled on a single particle basis [36–38]. To model the SHS drying of porous wood particles, Le et al., 2020 proposed and evaluated two models of effective diffusivity: moisture-dependent and temperature-dependent to account for the decrease in the drying rate in the second drying stage, when bound moisture is removed from the micropores and cellular cells [38]. In these effective diffusivity models, the magnitude of moisture diffusion was described either as a function of particles temperature (expressed by the Arrhenius equation) or particles moisture content (expressed by the
equation proposed by Khan et al., 2016 [39], Karim and Hawlader, 2005 [40]). A comparison of simulation results for both models with experimental data obtained applying a magnetic suspension balance system showed that the moisture-dependent effective diffusivity is more appropriate to be used in the diffusion model of wood particle SHS drying.

In a recent paper Tran, 2020 presented a mathematical model of SHS drying of ceramic particles in a packed bed. The drying kinetics of a single particle was simulated by applying the semiempirical Reaction Engineering Approach (REA), which uses the activation energy parameter to represent the difficulty of moisture removal from porous material compared with moisture evaporation from pure water droplet surface. The developed drying kinetics model was verified by experimental data and then combined with heat and mass transfer equations for solid and vapor phases in the packed bed. The final model of packed bed SHS drying lack verification with experimental data [41].

Due to the chosen semiempirical approach, direct application to droplet drying of the above-mentioned models [36–38] is not possible.

4.2. Modeling of Superheated Spray Drying in Laboratory and Pilot Plant Dryers

In 1980, Gauvin and Costin published a paper devoted to the theoretical analysis of SHS spray drying [42]. The authors presented a comparative theoretical study of open-air and closed SHS spray drying systems showing that in the case of SHS the size of the drying chamber may be significantly reduced. Moreover, the reduction in operating cost by 21.5% was possible by applying closed-loop steam drying instead of air drying in the open system.

The numerical modeling of SHS spray drying conducted by Crowe et al., 1985 showed that steam could be considered as a more effective drying medium than air due to higher heat transfer coefficients and higher specific heat [43]. In the proposed model, Crowe et al., 1985 assumed that slurry droplets are to dry only during periods of constant and decreasing drying rate, while the initial heating and steam condensation period has been neglected. To evaluate particles moisture content during the falling rate period the authors applied Equation (3), which was obtained experimentally via curve fitting to the relationship between the equilibrium moisture content and steam temperature for a wood particle. To calculate the rate of change of particles moisture content with temperature Equation (3) was differentiated (Equation (4)).

\[
W = W_c \exp\left(-2.37\tanh\left(\frac{T_p - T_s}{24.6}\right)\right),
\]

\[
\frac{dW}{dT_p} = -0.096 W_c \exp(-2.37\tanh\theta)\text{sech}^2\theta,
\]

where \(W_c\) is critical moisture content, \(T_p\) is the particle temperature, \(T_s\) is the saturation temperature and \(\theta = (T_p - T_s)/24.6\).

Equation (4) was then implemented into the energy equation of the droplet for the second drying stage (Equation (5)):

\[
\left(1 + \frac{W_{C_p}}{c_{ps}} \frac{dW}{dT_p} \frac{\Delta H}{c_{ps}}\right) \frac{dT_p}{dt} = \text{Nu} \pi k_s D_{ad}(T_g - T_p) / \rho_s c_{ps},
\]

The results of the simulation showed that the higher thermal capacity of SHS compared to hot air increases the droplets drying rate. Particle trajectories for SHS and air spray dryers were calculated and compared. In SHS dryer, large particles with diameters of 400 µm stack to the dryer wall immediately after they were injected by the nozzle, whereas for the same process conditions in air dryer particles with a size of 400 µm fall downward through the cylindrical part of the dryer and hit the wall only at the conical part close to powder discharge. The investigators explained this phenomenon by the reduced viscosity in steam and smaller drag force acting on the particles and suggested that SHS spray dryers should be designed with larger diameters compared with standard hot-air dryers.
The CFD model of SHS spray drying was developed by Frydman et al., 1999 [44]. For the continuous phase, i.e., the steam, the following set of partial differential equations has been solved:

- **Continuity equation for steam:**
  \[ \frac{\partial \rho_g}{\partial t} + \nabla \cdot (\rho_g \vec{V}_g) = S_M, \]  
  \[ (6) \]

- **Momentum balance equation for steam:**
  \[ \frac{\partial \rho_g \vec{V}_g}{\partial t} + \nabla \cdot (\rho_g \vec{V}_g \vec{V}_g) = -\nabla \cdot \vec{P} + \rho_g \vec{g} + F - \nabla \cdot \tau, \]  
  \[ (7) \]

- **Energy balance for steam:**
  \[ \frac{\partial \rho_g H_g}{\partial t} + \nabla \cdot (\rho_g \vec{V}_g H_g) = k_g \nabla^2 T_g + \frac{\partial P}{\partial t} + \nabla \cdot \vec{P} \vec{V}_g + S_H. \]  
  \[ (8) \]

For the discrete phase, i.e., droplets, following set of equations has been solved:

- **Droplet trajectories:**
  \[ \frac{\partial \vec{V}_p}{\partial t} = \frac{3 C_{drag} \rho_s (\vec{V}_s - \vec{V}_p)^2}{4 D_d \rho_p} + \frac{\rho_p - \rho_s}{\rho_p} \]  
  \[ (9) \]

- **Heat and mass transfer between steam and droplets:**
  \[ -\frac{dm_p}{dt} \Delta H = \alpha A_p (T_{g,\infty} - T_p). \]  
  \[ (10) \]

Since experiments and modeling have been conducted for pure water drying, the reduction in moisture evaporation rate during the falling drying rate stage was not taken into consideration. The initial steam condensation period was also neglected during the simulation. The model was validated using experimental data on the temperature profiles during steam spray drying of water droplets used as a model material.

Chauhan et al., 2020 developed a CFD model of a two-phase system including potassium carbonate droplets dispersed in SHS applying Openfoam® (OpenCFD Ltd., Bracknell, UK) solver, i.e., sprayFoam dedicated to discrete particles flow modeling. The model included droplets breakup and trajectory simulation, heat transfer between steam and droplets, droplets evaporation and boiling point elevation due to salt concentration within the droplets. The model does not take into consideration further droplet drying in the SHS; nevertheless, it provides a mathematical model of droplets flow and evaporation in SHS confirmed by experimental results [45].

Ducept et al., 2002 [46] elaborated the 2D CFD model of the SHS spray dryer and verified the results of the simulation with experimental data obtained on the pilot SHS spray dryer. The authors applied the mathematical model described in the work of Frydman et al., 1999 [44]. The particle size distribution determined experimentally has been introduced in the model, the standard k-\( \varepsilon \) model has been applied for turbulence calculation and to account for particles drying pure water evaporation has been assumed, which does not include the falling drying rate stage in the model. The mathematical model developed for the case of pure water evaporation was validated by applying experimental data on temperature distributions within the drying chamber. In the case of solids drying, the particles’ residence time in the drying chamber was measured and compared with simulation data. A special experimental setup was applied for particle residence time measurement grounded on the registration of conductivity of KCl solution introduced in the drying chamber close to the nozzle. After passing the drying chamber, the vapor was
condensed and the conductivity of the solution was measured. A high specific evaporating rate, i.e., 50 kg/m³ h was achieved during the study, indicating that the application of SHS as a drying medium for spray drying permits for reduction in spray dryer size.

The data gained in the study of Ducept et al., 2002 has been used by equipment manufacturer Techni Process to scale up the pilot plant SHS spray dryer from an evaporative capacity of 10 L/h to 40 L/h and build the prototype [47].

5. Experimental Studies of Superheated Spray Drying

5.1. Single Droplet Drying in Superheated Steam

The first study on the evaporation and drying of isolated droplets in SHS has been carried out by Trommelen and Crosby, 1970 [48]. The researchers studied the evaporation of single droplets of different types of materials, i.e., sucrose, tomato juice, coffee extract, milk, sodium sulfate, potassium nitrate and detergent slurry in both hot air and steam. It was found that when the inversion temperature of 250 °C is reached, the evaporation rate of droplets in the SHS becomes faster compared with hot-air drying. The authors investigated only the physical characteristics of the dried particles without analysis of the impact of steam drying on the degradation of thermally sensitive products.

The most recent study of SHS drying of isolated droplets for different types of materials: organic sugar—lactose and mannitol, proteins—whey protein isolate and ionic substance—NaCl was carried out by Lum et al. [49–51]. The single droplet drying experiments were performed by applying glass filament carrying a single droplet in the drying channel purged with SHS, the droplet drying history was monitored by a digital camera.

The authors observed incomplete drying of hygroscopic lactose droplets after 900 s of SHS drying at 110 °C, 130 °C and 145 °C under ambient pressure, whereas for hot-air drying, solidification of lactose droplets occurred after a drying time of 160 s at a temperature of 110 °C [49]. Due to a higher tendency for crystallization and lower hygroscopicity, it was easier to dry mannitol droplets than lactose; however, the solidification of mannitol was also not observed for SHS drying at 110 °C. The observed phenomenon has been explained by the saturated-equilibrium state, which is reached due to low driving force during SHS drying. Since the equilibrium moisture content of the material is directly related to the relative humidity of the drying medium, the equilibrium water activity of air and SHS at different pressure and temperature was calculated and compared. The relative humidity of the hot air is a ratio of the partial pressure of water vapor to saturated pressure. In the case of SHS, the ‘wetness’ of the drying medium might be expressed as a degree of saturation of water vapor calculated as a ratio of SHS operating pressure to the saturation pressure corresponding to the temperature of the SHS. The authors claimed that the ‘wetness’ of the steam may be reduced via two routes: greater superheating of steam or reducing the steam operating pressure [49].

During SHS drying, rapid precipitation was observed in the whey protein isolate droplets, which resulted in specific morphology of dry particles consisting of ultrafine spherical protein aggregates. The authors showed a significant effect of the application of SHS on droplet drying history regarding the droplet temperature, which reaches high values during the constant rate drying period. Based on the experimental results, the following conclusion has been drawn: steam drying may be applied for in situ particle crystallization with the formation of unique particle morphology; very fine crystals in the case of mannitol and hollow hopper-like crystals for nonorganic NaCl [52].

In the previous study of the same research group, additional specific features of superheated spray drying of multicomponent biological materials have been revealed [50]. Single droplet SHS drying experiments of milk have shown an increase in particle surface wettability. Subsequent exploration with pilot scale experiments revealed that an increase in surface wettability may be due to an increase in the porosity of the milk powder under superheated steam drying conditions [51].

The reason for increased particle surface porosity after SHS spray drying compared to hot-air drying is still unclear and requires further investigation.
5.2. Spray Drying by Superheated Steam in Laboratory and Pilot Plant Scale

Several works describe the experimental study of SHS spray drying in laboratory and pilot-scale dryers.

In 1983, Gauvin patented the method of SHS plasma spray drying, which may be applied to thermally resistant materials [53]. The proposed dryer consisted of a steam generation system: steam boiler and steam generator, plasma generator, solution feeding system, drying chamber and dry powder/steam separation system. SHS plasma was generated when SHS passed through an arc between the cathode and water-cooled anode in a commercial 50 kW Thermal Dynamics Plasma Torch. The inventors reported successful spray drying of heat-resistant materials applying SHS plasma at temperature 6000 K which has an enthalpy of 73.6 MJ/kg at pressure 1 atm and 71.5 MJ/kg at pressure 10 atm. Such high enthalpy permits us to achieve a very high drying rate at a significantly reduced plasma steam flow rate in the dyer. To obtain dry powders the amount of plasma steam needed for drying was estimated at 1/24 of moisture which must be evaporated from the product.

Raehse and Bauer in 1995 [54] patented an SHS spray drying method for drying of laundry detergent powders components: anionic surfactants, inorganic, and organic building materials, washing alkalis, fillers, and neutral salts, fabrics softeners and bleach activators. These materials are resistant to temperatures above 100 °C during superheated steam spray drying. The inventors focused on the drawbacks of SHS spray drying such as contamination of the dried powder by water vapor, which immediately condenses during the powder cooling stage increasing the final moisture content of the product. Raehse and Bauer proposed: (1) adding an auxiliary component capable to bind the moisture in the final product; (2) applying the fluidized bed as a subsequent treatment to the drying in SHS to homogenize the moisture content of the dried powder or; (3) including an additional drying stage to reduce final moisture content and improve free-flowing properties of the product. Successful spray drying of the detergent group materials with a feed concentration of about 50 wt.% under SHS temperature at the dryer inlet 190–300 °C and outlet 120–130 °C has been reported [54].

Islam et al., 2016, applied an SHS vacuum spray drying process at a pressure of 5–7 kPa (abs. pressure) and a temperature of 40–60 °C for the dewatering of orange juice [55]. Prior to drying, orange juice was mixed with maltodextrin at the following ratios (juice solids to maltodextrin solids): 60:40, 50:50, 40:60, and 30:70. The temperature of SHS supplied to the drier was 200 °C; however, the temperature of the product in the dryer was below the steam saturation temperature (40 °C for pressure 5–7 kPa). The dryer and cyclone walls were equipped with heating jackets with circulating water at a temperature of 50 °C to avoid powder deposition on the walls. The powder collected in the receivers was purged with dry air at a temperature of 45 °C. As a result, stable orange juice powder with low moisture content (2.29–3.35%) and water activity has been produced due to a greater heat gradient between steam and dried droplets than between hot air and droplets. The authors reported ca. 71% retention of ascorbic acid after SHS vacuum spray drying.

In the recent study of Lum, 2018 laboratory SHS spray dryer was applied for the dewatering of D-mannitol, NaCl solution and milk by SHS at temperatures of 140 °C and 180 °C under a counter-current flow regime [51,52]. The experimental installation included: a drying chamber, a T-section at the drying medium inlet to switch between SHS or hot air applied as a drying medium, a superheater, and a steam generator for steam supply. The drying chamber was covered by electric heating tapes and insulation to avoid steam condensation on the dryer walls. It was reported that periodic withdrawal of the product from the bottom conical part of the dryer by heated cone and double block valves does not prevent steam condensation within the product. Therefore, at the bottom of the drying chamber, a bleeding opening was applied to allow for the entrance of the air into the bottom part of the dryer and allowed for continuous removal of the product and avoided the steam accumulation in the conical part of the dryer (Figure 3a). Additionally, the drying chamber was equipped with thermocouples at different dryer heights to enable the measurement of
the temperature profile within the dryer. The application of SHS spray drying improved powder wettability for both instant skim milk and full cream milk powders: after SHS-SD powder wettability was 20 s and 38 s, whereas after standard hot-air drying—42 s and 76 s. A more porous surface was observed for particles obtained in the SHS-SD process, whereas after hot-air spray drying particles with lower surface porosity were produced (Table 1).

Figure 3. Scheme of SHS spray dryers with different methods of product collection: (a) air supply to the conical part of the dryer [51]; (b) powder collector with heated walls and filter [56]; (c) use of venturi nozzle and double cyclone separation stage [57].

In the experimental study of Fuengfoo et al., 2018 [56], maltodextrin was dried by applying an SHS spray dryer operated under atmospheric pressure at inlet steam temperatures of 160 °C, 170 °C and 180 °C. The temperature in the powder receiver was kept above the saturation temperature of the exhaust steam, i.e., 105 °C to avoid steam condensation at the surface of the dry particles (Figure 3b). Additionally, the thermostated rotary valve was applied for the discharge of dry powder from the cyclone to the powder collector. The authors analyzed the impact of the implementation of SHS as a drying medium on powder recovery and morphology. A comparison of the results for SHS and standard hot-air spray drying showed that product recovery was 48.5%, when SHS was applied, to 37% for hot-air drying (Table 1). This phenomenon has been explained by the higher heat transfer coefficient and heat capacity of the steam, which resulted in faster solid crust formation at the surface of the particles. The morphology of the maltodextrin particles obtained after SHS drying was described as spherical particles with inflated skin formed due to rapid moisture vaporization. After hot-air drying at similar drying conditions, the situation was the opposite: maltodextrin particles were spherical with wrinkled skin, which indicates a slow evaporation rate.
Table 1. SHS spray drying in the laboratory and pilot plant scale.

<table>
<thead>
<tr>
<th>Product</th>
<th>Equipment</th>
<th>Process Parameters</th>
<th>Product Properties</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrated orange juice</td>
<td>Nozzle type: 2 two-fluid nozzles;</td>
<td>Still/Steam: 40 NL/min;</td>
<td>- Moisture content: 2.29–3.35%;</td>
<td>[55,58]</td>
</tr>
<tr>
<td>(C. sinensis) + Maltodextrin DE12</td>
<td>Flow direction: co-current;</td>
<td>Vacuum in the drying chamber: 5 kPa;</td>
<td>- Product yield: 53–63%;</td>
<td></td>
</tr>
<tr>
<td>Solids content: 33 Brix%</td>
<td>Drying chamber wall temperature: 50 °C;</td>
<td>Saturated steam temperature: 40 °C;</td>
<td>- Glass transition temperature of powder: 61–86 °C;</td>
<td></td>
</tr>
<tr>
<td>Feed rate: 300 mL/h</td>
<td>Steam/product separation: in double wall cyclone, heated up by hot water (50 °C);</td>
<td>- Hygroscopicity: 0.143–0.195 g\text{H}_2\text{O}/g;</td>
<td>- Rehydration: 122–253 s;</td>
<td></td>
</tr>
<tr>
<td>Ratio of juice solids to maltodextrin solids: 60:40, 50:50, 40:60, and 30:70</td>
<td>Product collection: in the double wall receivers with entrance of air at temperature 45 °C</td>
<td>- Bulk density: 0.70–0.73 g/mL;</td>
<td>- D50: 6.02–7.75 μm</td>
<td></td>
</tr>
<tr>
<td>Instant skim milk</td>
<td>SHS Spray dryer size: D = 0.32 m, H = 3.1 m;</td>
<td>Inlet steam temperature: 140 °C;</td>
<td>- Powder morphology: spherical.</td>
<td>[51]</td>
</tr>
<tr>
<td>Solid content: 25 wt%</td>
<td>Flow direction: counter current;</td>
<td>Steam mass flow rate: 1.4 kg/h;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drying chamber wall temperature: &gt;100 °C;</td>
<td>Atomization pressure: 3 bar;</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>opening at the top and bottom of the dryer to allow for air entrance;</td>
<td>SHS Spray drying:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Product collection: via bleeding opening at bottom outlet of the dryer;</td>
<td>Atomization air flow rate: 40 NL/min;</td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Vacuum in the drying chamber: 5 kPa;</td>
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<tr>
<td></td>
<td></td>
<td>Saturated steam temperature: 40 °C;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full cream milk</td>
<td>As above</td>
<td>As above</td>
<td>- Wettability: SHS-SD: 38 s</td>
<td>[51]</td>
</tr>
<tr>
<td>Solid content: 25 wt%</td>
<td></td>
<td></td>
<td>- Solubility: SHS-SD: 83%</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- Surface fat content: SHS-SD: ca. 93%</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- Powder morphology: SHS-SD: particles with porous surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- SSD: less porous particle’s surface</td>
<td></td>
</tr>
<tr>
<td>Product</td>
<td>Equipment</td>
<td>Process Parameters</td>
<td>Product Properties</td>
<td>Reference</td>
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</tr>
<tr>
<td>D—Mannitol Solid content: 15 wt%</td>
<td>As above</td>
<td>SHS Spray drying: Inlet steam temperature: 140 °C and 180 °C; Steam mass flow rate: 1.4 kg/h; Atomization pressure: 3 bar;</td>
<td>Powder morphology: SHS-SD: spherical with fine crystal morphology SSD: spherical</td>
<td>[52]</td>
</tr>
<tr>
<td>Sodium Chloride, NaCl Solid content: 15 wt%</td>
<td>As above</td>
<td>As above</td>
<td>- Powder morphology: SHS-SD: mixture of cubic crystals, hopper like salt crystals and by-pyramidal crystals SSD: microspheres of cubic structure crystals</td>
<td>[52]</td>
</tr>
<tr>
<td>Maltodextrin DE 10 Solid content: 30% w/v; feed flow rate: 5 mL/min;</td>
<td>SHS Spray dryer size: D = 0.25 m, H = 0.8 m (Cylinder = 0.5 m, Conical = 0.3 m); Nozzle type: two-fluid nozzle Flow direction: co-current Product/steam separation: glass cyclone with powder collector equipped with cylindrical stainless-still filter, auxiliary heater and steam outlet.</td>
<td>SHS Spray drying: Inlet steam temperature: 160, 170, 180 °C; Steam velocity: 14–15 ms; Steam pressure: 20 kPa (gauge); Atomization pressure: 2 bar; Product discharge: Temperature 105 °C;</td>
<td>- Product yield: SHS-SD: 38–48% SSD: 32–37% - Powder morphology: SHS-SD: spherical SSD: wrinkled</td>
<td>[56]</td>
</tr>
<tr>
<td>Skim milk concentrate Solid content: 0.27 kg/kg; Feed flow rate: 1.14 kg/h</td>
<td>SHS Spray dryer size: D = 0.2 m, H = 0.65 m (Cylinder = 0.45 m, Conical = 0.2 m); Flow direction: co-current; Nozzle type: pressure; Product/steam separation: dilution by air in the two stage cyclones equipped with annular Venturi nozzle</td>
<td>SHS Spray drying: inlet steam temperature: 250 °C; outlet steam temperature: 130–160 °C; Steam flow rate: 10 kg/h; Atomization pressure: 1 MPa; Product/steam separation: Relative humidity: 73.8–89.6%; Temperature: 31.5–37.9 °C; Product discharge: Relative humidity: &lt;30%; Temperature: &lt;35 °C;</td>
<td>- Moisture content: SSD: 3.33% SHS-SD: 6.80% - Product yield: ca. 30–40% - D50: ca. 15–25 μm - Powder morphology: SHS-SD: wrinkled SSD: wrinkled</td>
<td>[57]</td>
</tr>
<tr>
<td>Product</td>
<td>Equipment</td>
<td>Process Parameters</td>
<td>Product Properties</td>
<td>Reference</td>
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<tr>
<td>Lactose</td>
<td>As above</td>
<td>As above</td>
<td>- Moisture content: SSD: 5.17% SHS-SD: 4.48%</td>
<td>[57]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Product yield: 5.9% - D50: ca. 15–25 µm - Powder morphology: SHS-SD: mostly spherical SSD: irregular</td>
<td></td>
</tr>
</tbody>
</table>

| Micellar casein concentrate | Solid content: 0.10 kg/kg; Feed flow rate: 0.72 kg/h | As above | As above | - Moisture content: SSD: 6.13% SHS-SD: 6.14% | [57] |
|                            |                                                       |          |          | - Product yield: ca. 30–40% - D50: ca. 15–25 µm - Powder morphology: SHS-SD: wrinkled SSD: wrinkled |

| Whey Protein Isolate       | Solid content: 0.10 kg/kg; Feed flow rate: 0.71 kg/h | As above | As above | - Moisture content: SSD: 6.67% SHS-SD: 8.09% | [57] |
|                            |                                                       |          |          | - Product yield: ca. 30–40% - D50: ca. 15–25 µm - Powder morphology: SHS-SD: wrinkled SSD: wrinkled + partially fractured particles |

| Maltodextrin DE < 3        | Solid content: 0.15 kg/kg; Feed flow rate: 0.93 kg/h | As above | As above | - Moisture content: SSD: 5.00% SHS-SD: 9.59% | [57] |
|                            |                                                       |          |          | - Product yield: 45% - D50: ca. 15–25 µm - Powder morphology: SHS-SD: wrinkled SSD: irregular |
Table 1. Cont.

<table>
<thead>
<tr>
<th>Product</th>
<th>Equipment</th>
<th>Process Parameters</th>
<th>Product Properties</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gum Arabic Seyal</td>
<td>As above</td>
<td>As above</td>
<td>- Moisture content:</td>
<td></td>
</tr>
<tr>
<td>Solid content: 0.10 kg/kg; Feed flow rate: 0.87 kg/h</td>
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<td></td>
<td>SSD: 10.06%</td>
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<td></td>
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<td>SHS-SD: 9.20%</td>
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<td></td>
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<td></td>
<td>- Product yield: ca. 30–40%</td>
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<td></td>
<td></td>
<td></td>
<td>- D50: ca. 15–25 µm</td>
<td></td>
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<td></td>
<td></td>
<td>- Powder morphology:</td>
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<td></td>
<td></td>
<td></td>
<td>SHS-SD: wrinkled</td>
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<td></td>
<td></td>
<td></td>
<td>SSD: irregular</td>
<td></td>
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<tr>
<td>Soy Protein Isolate</td>
<td>As above</td>
<td>As above</td>
<td>- Moisture content:</td>
<td></td>
</tr>
<tr>
<td>Solid content: 0.05 kg/kg; Feed flow rate: 1.05 kg/h</td>
<td></td>
<td></td>
<td>SSD: 7.89%</td>
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<td></td>
<td>SHS-SD: 8.74%</td>
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<td></td>
<td>- Product yield: ca. 30–40%</td>
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<td></td>
<td></td>
<td></td>
<td>- D50: ca. 15–25 µm</td>
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<td></td>
<td>- Powder morphology:</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>SHS-SD: wrinkled</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SSD: wrinkled</td>
<td></td>
</tr>
<tr>
<td>Coffee Extract</td>
<td>As above</td>
<td>As above</td>
<td>- Moisture content:</td>
<td></td>
</tr>
<tr>
<td>Solid content: 0.05 kg/kg; Feed flow rate: 1.05 kg/h</td>
<td></td>
<td></td>
<td>SSD: 5.73%</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>SHS-SD: 5.02%</td>
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<td></td>
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<td>- Product yield: 24.6%</td>
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<td></td>
<td>- D50: ca. 15–25 µm</td>
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<td></td>
<td>- Powder morphology:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SHS-SD: spherical</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SSD: irregular</td>
<td></td>
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</tbody>
</table>

1 SHS-SD—superheated spray drying, 2 SSD—standard spray drying.
A recent study by Linke et al., 2022 showed the possibility to apply SHS spray drying to heat-sensitive dairy (skim milk concentrate, lactose, whey protein isolate, micellar casein concentrate) and food (maltodextrin, gum Arabic seyal, soy protein isolate, coffee extract) products [57]. To avoid steam dilution by air entrance into the drying chamber, the feed was atomized by pressure nozzle. The steam/product separation process was carried out as a two-stage process (Figure 3c). The mixture of steam and dry particles leaving the drying chamber were sucked to cyclone equipped with an annular Venturi nozzle, where the stream was diluted with air to avoid steam condensation and reduce the temperature to minimize powder overheating. Thus, in the first cyclone relative humidity was in the range 73.8–89.6% and the temperature was 31.5–37.9 °C, in the second cyclone the final separation of air/steam stream from dry particles and discharge of the powder was carried out at relative humidity below 30% and temperature below 35 °C. The final product properties of SHS-spray dried powder were analyzed and compared with standard process. The moisture content of powders after SHS-SD was in the range from 4.48% for lactose to 9.59% for maltodextrin, which was in the same range as after the standard spray drying process or close to the initial moisture content in the raw materials. A slight browning of skimmed milk powder, micellar casein concentrate and coffee extract powder was observed after SHS-SD process; however, in the case of maltodextrin and whey protein isolate, no change in color was observed in comparison with the initial raw powder. Linke et al., 2022 [57] observed wrinkled particles structure after steam spray drying for all products, except coffee extract powder. These results were contradictory to findings reported by Fuengfoo et al., 2018 [56] and Lum, 2018 [51], who obtained particles with spherical inflated structures after SHS drying. Linke et al., 2022 applied pure SHS as a drying medium, whereas in both studies of Fuengfoo et al., 2018 [56] and Lum, 2018 [51] the SHS was diluted by air entrance due to the application of a two-fluid nozzle for feed atomization or due to the presence of openings in the drying chamber. Therefore, wrinkled particle structure after pure SHS drying was explained by the absence of solid crust formation during droplet drying in SHS due to the lack of a resistant gas film around the droplets [57]. The application of SHS diluted by air resulted in fast solid crust formation around the droplets in the initial stage of drying due to high droplet temperature (equal to steam saturation temperature) in the constant drying rate period, which resulted in rapid moisture evaporation within the droplets, pressure build-up and particles inflation. As reported by Fuengfoo et al., 2018 spray drying by hot air at the same inlet temperature (i.e., 160 °C) as during SHS drying, produced wrinkled particle structure due to a lower drying rate of droplets in the first drying stage, since in hot-air drying droplet temperature is close to the wet-bulp temperature, which is much lower compared with steam saturation temperature. The product yield after SHS-SD varied from 5.9% for lactose to 45% for maltodextrin [57]. The authors reported the highest loss of product due to powder sticking to the walls observed at the conical part of the drying chamber and in the inlet of the first cyclone. According to Bhandari et al., for laboratory scale spray dryer product yield above 50% is considered to be at the acceptable level [59]. The product yield for SHS-SD reported by both Linke et al., 2022 [57] and Fuengfoo et al., 2018. [56] was below 50% indicating that further research and improvement of steam/dry powder separation and product collection stage is still required.

Another pilot-scale SHS spray dryer has been built and operated by ENSIA in France; the Techni Process SHS spray dryer has an evaporation capacity of 50 kg/h [60]. An SHS spray dryer on an industrial scale with a capacity of 4–6 t H2O/h was built by Henkel AG & Co. KGaA and applied for drying of heat resistant material such as detergents [60,61]. The 28 m height spray dryer operated with an inlet steam temperature in the range of 120–350 °C. The application of SHS as a drying medium gave the possibility to reduce air emissions and enabled the operation of the spray drier in the highly populated area [60].

Table 1 summarizes the examples of the application of SHS spray drying in the laboratory and pilot scale and provides the following information: type of product, equipment
applied for drying (size of spray dryer, type of nozzle, steam/powder separation method, powder collection method), process parameters and key product properties.

6. Perspectives of Superheated Steam Spray Drying

An advantage that SHS spray drying shares with all applications of SHS in drying is the ability to recover most of the energy used for evaporation and reduce the energy used to evaporate 1 kg of moisture.

Since the drying process in the SHS produces steam equal to the amount of water evaporated, it is necessary to find a useful application for this excess steam in the process plant. If this steam is used outside the drying process, the recovered heat is not included in the drying energy costs, leading to a reduction in energy consumption for evaporation.

The drying process is one of the most energy-demanding unit operations since latent heat for water vaporization is 2250 kJ/kg water at 100 °C. The theoretical energy consumption of a properly designed and operated hot-air dryer is 2620 kJ/kg water evaporated; however, typical industrial dryers consume above 4500 kJ/kg water [10]. For industrial spray dryers, energy consumption varies from 4500 to even 11,500 kJ/kg water [62]. In the hot air-drying system energy recovery is limited due to the low-temperature level of waste energy. Baker and McKenzie, 2005 estimated that about 29% of the energy supplied to industrial spray dryers is wasted [63]. When superheated steam is applied as an energy carrier the waste energy can be reused after drying in a closed loop drying system, where exhaust steam after leaving the spray dryer and product separation is heated up in a steam generator [64]. In such a configuration, the specific energy consumption of the dryer may be decreased to about 3600 kJ/kg water (Figure 4a). Moreover, excess steam generated during moisture evaporation may be re-compressed by applying newly developed compression technology [65] to increase the temperature level of the waste heat and reuse it in the spray dryer as shown in Figure 4b. In this case, the specific energy consumption of the SHS spray drying process may be reduced to 540–720 kJ per kg water [65]. Taking into consideration that drying-related energy demand for industrial dryers may cover from 12% to 15% of the total energy demand of the manufacturing process [66], which, in combination with other concerns such as insecurity in the energy sector connected with threats of fossil fuels supply disruptions, dramatically increasing energy prices as well as climate change issues, make application of SHS for spray drying even more attractive.

In the SHS drying processes, to make the process more energy-efficient, the generated steam is either collected and diverted to other uses or condensed to recover latent heat. In this process, it is possible to collect dust and valuable or harmful components instead of releasing them into the environment. Conducting the drying process in an oxygen-free atmosphere also contributes to reducing product oxidation, limiting the risk of explosions.

SHS drying processes can be classified into three types differing by the pressure at which drying is carried out. Low pressure in which the pressure in the drying chamber is in the range of 5–30 kPa (abs.), near atmospheric operating at pressures close to 100 kPa (abs.) and high pressure in which the pressure exceeds 300 kPa (abs.). Together with the pressure, the saturated steam temperature and the maximum temperature, to which the dried material is heated, change.

Low-pressure SHS drying is used for the drying of temperature-sensitive materials as it allows the process to be carried out at relatively low temperatures. Near atmospheric and high-pressure processes can be used for drying materials with higher temperature resistance.

Reports on spray drying in SHS are few. There have been a few theoretical papers analyzing the spray drying process in SHS [44]. The model results were verified by pilot scale experiments using water to check the heat and mass balance. Small-scale spray drying was studied by Lum, 2018 [51], Fuengfoo et al., 2018 [56], Islam et al., 2017 [55], Linke et al., 2022 [57]. They demonstrated the feasibility of the process in SHS but, more importantly, made very important observations about the product obtained.
SHS drying affects the mechanism of moisture transport in the dried particle, Lum et al., 2019 [49] observed surface (potentially structural or compositional) changes which resulted in changes to the hydrophilicity of the surface of the dried particle as a result of contact with SHS. By using the potential of SHS as a spray-drying medium, multi-component particles with specific properties can be produced. In general, SHS spray drying yields higher porosity of the products, better rehydration behavior and new structural and functional properties.

The SHS spray drying tests performed did not, with one exception, exceed the pilot scale. In all reports, one can find information signaling the engineering challenges posed by spray drying in SHS. The drying chamber and product discharge system must be carefully thermally insulated to avoid uncontrolled condensation. Regardless of the operating pressure, the drying chamber must be carefully separated from its surroundings, so product removal is an engineering challenge. Before the product is brought out, it must be separated from the steam. At no stage must condensation be allowed on the walls or product.

Figure 4. Different configuration of SHS spray dryers: (a) standard SHS spray dryer and; (b) SHS spray dryer with energy recovery (Based on [65]).

7. Conclusions

This review summarizes the level of development of superheated steam spray drying technology, focusing on the advantages and theoretical background of SHS steam drying, followed by an overview of mathematical models of single particles drying in SHS as well
as simulations performed on the laboratory and pilot scale dryers. In the next part of the paper, the results of experimental works on SHS spray drying are discussed, covering the special requirements for dryer construction and particles–steam separation equipment and providing analysis of the effect of steam drying on product properties, giving the example of products which could be dried applying SHS.

The works presented above fill the gap in the knowledge considering the application of SHS in the spray drying systems; however, the works are limited to the numerical modeling only [42,44] or to the single droplets drying experiments [48–51], which do not reflect the full picture of droplets behavior within the real spray dryer. A few experimental works on SHS spray drying [54–57] present valuable information about the process; however, they are rather general and without complex analysis of energy efficiency and product quality in SHS spray drying. To the best of our knowledge, there is no study on a detailed CFD model of SHS spray drying accounting for complete droplet drying history (initial heating and condensation, constant drying rate period, falling drying rate period) reported in the literature. Taking into account the advantages of superheated drying and the limited application of this technology in spray drying systems, there is still a high potential for further research in this area.

Author Contributions: Conceptualization, P.W.; writing—original draft preparation, M.S.; writing—review and editing, M.S., P.W. and M.W.W.; visualization, M.S. All authors have read and agreed to the published version of the manuscript.

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

Nomenclature

\[ A_p \] particles area (m²)
\[ C_{drag} \] drag coefficient
\[ c_p \] specific heat of liquid phase (J kg⁻¹ K⁻¹)
\[ c_{pg} \] mean superheated steam heat capacity (J kg⁻¹ K⁻¹)
\[ c_{ps} \] specific heat of solid phase (J kg⁻¹ K⁻¹)
\[ D \] dryer diameter (m)
\[ D_d \] droplet diameter (m)
\[ F \] body force (N)
\[ g \] gravitational acceleration (m s⁻²)
\[ \Delta H \] latent heat of vaporization (J kg⁻¹)
\[ H \] dryer height (m)
\[ H_g \] specific enthalpy of steam (J kg⁻¹)
\[ K \] proportion factor in eq. 2
\[ k_g \] thermal conductivity of steam (W m⁻¹ K⁻¹)
\[ m_{max} \] maximum drying rate (kg s⁻¹)
\[ m_p \] mass of particle (kg)
\[ m_s \] mass of solid phase (kg)
\[ N \] dimensionless parameter, relative variation of heat transfer coefficient with pressure
\[ N_{q} \] dimensionless number, ratio of amount of heat transferred by convection to the amount of heat introduced by superheated steam as a sensible heat
\[ Nu \] Nusselt number
\[ P \] total pressure (Pa)
\[ P_{op} \] optimum superheated steam pressure (Pa)
\[ R_{Nq} \] dimensionless function
\[ S_H \] source term for heat production (J s⁻¹ m⁻³)
\[ S_i \] inlet sectional area (m²)
\[ S_M \] source term of heat production (kg s⁻¹ m⁻³)


