engineering proceedings

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Proceeding Paper

Recent Advances in Particle Fluidization †

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† Presented at the 4th International Electronic Conference on Applied Sciences, 27 October–10 November 2023; Available online: https://asec2023.sciforum.net/.

Abstract: Recent advances in particle fluidization focus on improving the efficiency and control of various processes used in different industries. New technologies, such as spouted beds and circulating fluidized beds, have emerged to improve particle distribution. Additionally, the integration of computational fluid dynamics (CFD) simulations and other advanced technology leads to the effective observation of particle fluidization behavior and up-scaling of fluidized beds. In this paper, we aim to give a thorough analysis of studies from various research groups in the field of particle fluidization. The fundamentals of fluidization, recent advanced techniques, models and simulations, and application of the process will be emphasized. Moreover, it discusses various aspects regarding the challenges and opportunities of the fluidization process. Advances in particle fluidization hold great promise for improving industrial processes and enabling technologies in various industries.

Keywords: particle fluidization; fluidized bed; CFD

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Citation: Balag, J.; Franco, D.A.T.; Miral, V.G.; Reyes, V.; Tongco, L.J.; Lopez, E.C.R. Recent Advances in Particle Fluidization. *Eng. Proc.* **2023**, *56*, 62. https://doi.org/10.3390/ASEC2023-15321

Academic Editor: Francesco Arcadio

Published: 26 October 2023

1. Introduction

Particles, such as powder, sand, and grain, play a significant role in various engineering processes. Through the years, particle fluidization has gained attention from researchers as an interesting topic to focus on. Today, the process is widely used in various applications, such as chemical and petrochemical operations, coal combustions, and fluid catalytic processes [1]. This phenomenon focuses on particle behavior, where powders act like a fluid under certain circumstances. The process occurs as a gas or liquid flows through a bed of solid particles, causing them to exhibit a fluid-like behavior. In the fluid state, the material becomes buoyant and appears to move, similar to boiling liquid or the air of a suspended material. This unique behavior is due to the balance between the gravitational force exerted on objects and the water flow [2].

Advances in experimental techniques and numerical simulations have led to a deeper understanding of the complex particle fluidization process. Researchers have investigated many aspects of fluids, including the transition from a fixed bed to a fluidized system, particle hydrodynamics and flow behavior, bed expansion, and porosity, and the effect on the fluidization properties of the product [3–5]. This means that the comprehension of particle fluidization is an avenue for developing various industrial processes. Moreover, it allows scientists, researchers, and engineers to take part in improving the efficiency of technologies. This constitutes the enhancement of heat and mass transfer rates, increased competence of reactors, and more effective nanoparticle operations.

2. Fundamentals of Particle Fluidization

Fluidized beds are composed of solid particles held aloft by a flowing fluid, resulting in a fluidic motion of the solid particles. The remarkable ability of fluidized beds to promote efficient mixing and heat transfer has led to their widespread adoption in industries, such as power generation, chemical processing, and pharmaceutical production [6]. Furthermore, there is a growing interest in utilizing gas–solid beds in concentrated solar thermal power plants to optimize heat transfer.

2.1. Fluid Dynamics

Fluid dynamics pertains to the movement of substances characterized as fluids and their interactions with boundaries during flow [7]. Concerning particle fluidization, the motion of a fluid in the process is an important key factor. The fluidization velocity is a crucial operational parameter that impacts both the fluidization hydrodynamics and the granules' growth, playing a pivotal role in achieving uniform powder mixing. The fluidization velocity has a notable influence on the behavior of granulation and the final distribution of particle sizes, primarily by affecting the drying capacity [8]. During the initial stages of granulation, higher fluidization velocities have been observed to lead to a faster granule growth rate due to increased collision frequency and energy between the granules. However, larger granules are formed when the fluidization velocity is low due to the reduced shear force. In a batch fluidized bed granulation process, inherent instability is present.

The properties of solid particles themselves are important factors in fluid dynamics. The size, shape, density, and surface roughness of particles influence how they interact with the fluid, altering the drag forces and overall flow behavior. Smaller particles are more prone to entrainment, but irregular shapes might promote agglomeration and impede consistent fluidization. The parameters of the fluidizing gas, such as density, viscosity, and velocity, have a significant impact on fluid dynamics. The density of a gas influences buoyant forces, whereas viscosity determines the ease with which particles flow through a fluid. Variations in gas velocity cause transitions between flow regimes, influencing bed expansion and hydrodynamic behavior.

In fluid dynamics, the size and geometry of the fluidized bed system are critical. The distribution of gas and particles is influenced by bed height, diameter, and aspect ratio, which affects the mixing efficiency and pressure drop. Furthermore, the existence of internals, baffles, or draft tubes can change flow patterns, influencing particle behavior and fluidization dynamics. The fluidization regime used, whether bubbling, slugging, or turbulent, has a direct influence on fluid dynamics. Gas velocity, particle size, and bed characteristics control transitions between these regimes. Each regime has unique hydrodynamic properties that influence particle behavior, mixing, and heat/mass transmission.

The interactions of solid particles in the bed have a substantial impact on fluid dynamics. Cohesive forces caused by particle size distribution and interparticle cohesion can result in agglomeration or clustering. Repulsive forces, on the other hand, might be caused by electrostatic charges or surface qualities, impacting particle dispersion and overall bed stability. Fluidization behavior is influenced by the interaction of gas and solid particles. Drag forces caused by particle and gas motion dictate particle velocity and bed expansion. Furthermore, particle–wall interactions influence particle dispersion near the wall, impacting flow patterns and mixing.

Temperature, pressure, and gas composition, for example, can all have a substantial impact on fluid dynamics. Elevated temperatures can modify fluidization behavior by changing particle characteristics or causing chemical reactions. Variations in gas composition can change the gas density and viscosity, which can, therefore, affect the fluidization dynamics. The number of solid particles in the bed, which is frequently defined by bed loading or particle concentration, has a significant impact on fluidization dynamics. Increased particle concentrations can cause more interactions, particle–particle collisions, and slowed fluidization. It is critical to choose and adjust the particle concentration correctly in order to achieve the required fluidization behavior.

Computational fluid dynamics (CFD) advances have transformed the study of fluid dynamics within fluidized beds. CFD simulations reveal particle trajectories, fluid flow patterns, and pressure distributions. These simulations provide a virtual platform for experimenting with different operating conditions and system configurations, assisting in the design and optimization of fluidized bed processes.

2.2. Hydrodynamics

Fluidized bed hydrodynamics, which include complicated particle–fluid interactions, regime transitions, mixing, and segregation processes, have a substantial influence on process efficiency and product quality. Fluidized beds are dynamic devices that suspend solid particles in a fluid (usually gas) through fluidization. Fluidized beds are vital in applications, such as chemical reactions, combustion, drying, and particle coating, because to their peculiar condition, which allows for efficient mass and heat transmission. Understanding the complex hydrodynamic behavior of fluidized beds is critical for improving the performance and constructing efficient procedures.

As gas velocity increases, fluidized beds display diverse flow regimes: fixed bed, bubbling, slugging, turbulent, and transport regimes. These regimes are distinguished by distinct particle behaviors, bed expansion patterns, and pressure drop patterns. Regime transitions in the bed are influenced by gas velocity and particle characteristics, which affect mixing, heat transmission, and reaction rates. Fluidized beds encourage particle mixing, resulting in consistent solid–gas contact and reaction rates. Particle segregation, on the other hand, can occur owing to variances in size, density, and form. Segregation has an influence on product quality and efficiency, necessitating mitigation techniques.

Fluidized beds with efficient gas–solid contact improve heat and mass transfer, making them excellent for reactions and combustion. The dynamic mobility of particles guarantees that the solid–gas contact is constantly renewed, allowing for fast response rates and enhanced process efficiency. Rapid changes in hydrodynamics can cause pressure variations, which can compromise system stability and dependability. Regime transitions, particle interactions, and gas dispersion within the framework all contribute to these variations. Control techniques are required to keep the system running smoothly.

Variations in particle form, size, and density distributions can substantially affect the behavior of mixtures that include sand and biomass as component substances. These distinctions have a considerable impact on the fluid dynamics of the binary mixture [9]. Cloete et al. revealed that the particle size used within the reactor substantially impacts the degree to which there is dependence on grid resolution in fluidized bed reactor simulations, and they utilized the standard two-fluid model (TFM) technique. This was discovered in the study that they conducted [10]. The typical approach of setting the cell size in accordance with the particle size has been proved to be significantly incorrect, as the criteria for the grid become less stringent as the particle size grows. The results demonstrated this to be the case. These findings show that when larger particles are exploited, it becomes viable to simulate industrially relevant reactor sizes using existing computer models and resources.

3. Recent Advances in Particle Fluidization Techniques

Particle fluidization has a significant role in advancing innovative technologies that enhance process efficiency in different economic industries. There have been developments in reactor designs and novel equipment that can be integrated into experimental research and existing processes. In optimizing fluidization strategies, advanced computational models have been developed to understand the behavior of fluidized systems.

3.1. Fluidized Bed

The fluidized bed is the most known contacting technique in the processing industry, including oil refinery plants. The principal advantages involve temperature gradients induced by the thoroughly mixed particles, scalability for small- and large-scale operations, and constant processing. The process is employed for several widely recognized operations, such as the cracking and reforming of hydrocarbons, the carbonization and gasification of coal, the roasting of ore, the cooking of metals, the production of aluminum, the melamine, and the preparation of coatings. Considering their beneficial heat transmission features, fluidized beds are frequently used in multiple industrial procedures.

Many essential uses for fluidized beds involve reactions with significant thermal effects, and high heat production or removal rates may result. Some applications include polymerization in producing polyethylene, fluid catalytic cracking, and fluidized bed coal combustion. A simulation study by [11] utilized a fluidized bed to investigate the hydrodynamics and heat transfer employing a computational fluid dynamics–discrete element method. Analysis was conducted on how the fluidized bed's hydrodynamics and thermal behavior were affected by the gas superficial velocity and bed aspect ratio. Greater particles circulated upward in the central region at higher initial bed heights, while enhanced particle circulation was shown at higher superficial velocities. The fluidized bed becomes more isothermal when the surface gas velocity and aspect ratio rise. The variety of particles, both with and without heat generation, appears to impact how heat transfers. In addition to the excellent heat transfer properties, heat is effectively transferred from very active particles through the gas phase to inactive particles.

The computational fluid dynamics–discrete element method was employed in another study [12] in a fluidized bed rotor to examine how the liquid phase's presence affected the particle dynamics and contact time. When comparing the dry process simulation results to the simulations with liquid injection, it is clear that the liquid significantly impacts particle dynamics. Average particle velocity and contact time increase due to the development of liquid bridges and the forces generated by a viscous fluid in the liquid layer. A novel prototype that comprises capillary and viscous forces was used to analyze particle coating, including particle advancement and drying. It also showed how liquid injections and binder solutions impact the unit's performance.

3.2. Spouted Bed

In a spouted bed, the fluidizing medium passes through a narrow opening called the fluid intake located in the center of the vessel's base. Before the particles cascade into the space above the bed, termed the fountain, they are carried up the bed through the center region known as the spout. Then, solids are circulated through the annulus, a dense region outside the bed. Similar to fluidized beds, significant variables affect how the spout develops within the bed. These variables include the inlet flow rate, spout dimension, and solids' physical characteristics. Modifying these settings may substantially impact how the bed and spout behave [13].

Recent research utilized spouted beds for nuclear fuel applications like coatings; it was discovered that spouted beds could help with deposition timing, surface temperature control for spherical substrates, and precursor gas concentration, all of which could be used to optimize the crucial PyC (pyrolytic carbon) coating properties. The study utilized different heights of spouted beds that helped investigate crystal formation, the different pores, and the precursor particle-fluidized concentrations of coatings. The spouted bed reactor affected the texture and chemical properties of the concentrations, thus making it a possible enhancer of different coatings in said industry [14]. Additionally, spouted bed reactors have an incredibly significant role in drying production because of their higher efficacy than traditional fluidized bed drying. Also, it effectively dries grainy and coarse particles and has the potential to dry heat-sensitive materials and perform several kinds of chemical unit operations. Modern improved spouted beds can provide constant residence time, little wear and tear, favorable mixing of materials, and other sensible performance. They can also dry paste and powder materials when the particles are fluidized [15].

3.3. Circulating Fluidized Bed

One of the most commonly used technologies is the circulating fluidized bed (CFB) in the sector of energy due to several benefits of mass transfer and transfer heat rates, constant temperatures of the reactor, prolonged contact time of the gas particles, restricted pollutant outflow, and fuel adaptability [16]. It has been demonstrated that a CFB with a computational fluid dynamics (CFD) framework influences the entirety of the biomass gasification process. When comparing predicted and measured pressure distributions up the riser of the gasifier, there is good agreement due to the variable particle characteristics and gas velocities during the solids recirculation in a CFB system [17].

In another study regarding biomass gasification, the effect of bed temperature and the nature of fluidizing gas on the hydrodynamic parameters of olivine particles were experimented with. The terminal velocity was not affected by varying temperatures; hence, rigorous studies should be conducted because of the scarcity of the literature at high temperatures. Moreover, a regular CFB and a conventional circulation fluidized bed (CCFB) were analyzed at ambient temperature. The CCFB was operated under terminal velocity, and the regular CFB was operated beyond the particle terminal velocity. The solid hold-up of the conventional circulating fluidization was significantly greater than conventional fluidization, as determined by a review of the hydrodynamics. Solid hold-up rises with a rise in the solid circulation rate and a fall in the surface velocity of the liquid. In conventional circulating fluidized beds, particle–particle interaction is thought to be greater. Additionally, the performance of a CFP is dependent on gas and the particles. An increased rate of this mixture will contribute to the efficient dispersion of the reactants. On the other hand, an insufficient mixture of this may result in emissions of hydrocarbons. Therefore, it is essential to have an in-depth knowledge of the mixing behavior to achieve good combustion efficiency and emission management. A rectangular CFB with an area of 150 mm × 300 mm with a height of 2.1 m was utilized to investigate the fluidization of air and fuel particles at different flow speeds. The CFB system was found to have reduced back mixing in the riser section, wherein the pressure increased, and the circulation of solid fluidized particles increased [18].

3.4. Liquid Fluidization

In a study by Di Renzo et al., pressure variations were utilized as a segment of a gasification chemical looping method to assess the quality of bubbling fluidization in beds of oxygen carriers [19]. The objective was to evaluate the effectiveness of using pressure changes to monitor and detect any issues. The ultimate goal of this evaluation was to treat biogenic waste streams and utilize them as feedstock for the production of liquid biofuel. By doing so, the generation of toxic ashes, which cause a gradual loss of fluidity and agglomeration, could be reduced. The study successfully developed the hydrodynamics of a fluidized bed of wheat straw through the implementation of recommended pretreatment techniques.

Regarding microprocessing and microfluidic technology fundamentals, Sastaravet et al. made significant progress in understanding this topic by experimentally measuring the hydrodynamics and solid circulating velocity of a small-scale circulating liquid-fluidized bed [20]. The study utilized particle image velocimetry (PIV) to determine that the transition velocity closely matched the particle terminal velocity. Additionally, the researchers investigated the influence of solid archives, size, and density of the particles.

As per Chew et al., the processes involved in forming bubbles and transferring oxygen mass were thoroughly examined. Their team also investigated the interactions between solid particles, liquid motion, and gas bubbles [21]. Notably, incorporating ring- and cylinder-shaped media into the bubble column and air-lift reactor configurations resulted in a notable increase in the coefficient of mass transfer t, represented as K_La.

4. Advanced Modeling and Simulation of Particle Fluidization

Recently, advancements have been made in scaling-up processes based on established theoretical foundations. Two models, population balance models (PBMs) and computational fluid dynamics (CFD), have played a significant role in enhancing previous attempts at scaling laws and reduced-order models. By integrating CFD models with experimental methods, it has become feasible to eliminate at least one intermediate scale-up unit, resulting in a three-year reduction in development time and substantial cost savings totaling millions of dollars [22].

CFD modeling relies on fluid mechanics principles and employs numerical methods and algorithms to address fluid flow-related problems. These equations are governed by mass conservation, energy conservation, and momentum [23]. Currently, two commonly used simulation approaches are Euler–Euler and Euler–Lagrange, chosen based on the frame of reference used to solve the equation of motion. In the Euler–Lagrange simulation, individual particle movements are tracked. The first simulation of a fluidized bed using the Euler–Lagrange method was introduced by Tsuji et al. in 1993, employing a combined numerical approach known as CFD-DEM (CFD and discrete element method). This approach tracks the direction of each particle [11]. CFD-DEM is considered a crucial technique for studying fluidization properties.

Several investigations [12,24–29] discussed the advancement and utilization of computational tools. In one study [30], a model called Computational Fluid Dynamics-Discrete Element Method (CFD-DEM) was employed to explore the dynamics of fluidized beds and heat transfer dynamics. This study aimed to analyze the possible outcomes of exothermic gas–solid processes by investigating the effects of fluidization velocity, bed height, and heat source distributions. The findings indicated that the fluidization velocity and bed aspect ratio significantly influenced fluid flow dynamics and temperature distribution. These results underscore the crucial role of multiphase flow in facilitating heat transfer.

In a separate experiment conducted by Prakotmak et al. [31], they utilized a computational technique called CFD-DEM to replicate the movement of materials within a fluidized bed rotor granulator. The objective was to investigate the influence of the liquid phase on the behavior of particles and their contact time. The researchers analyzed the coating of particles, encompassing their growth and drying, using a novel model that incorporated capillary and viscous forces. This model provided insights into the effects of liquid injection and binder solution on the performance of the granulator.

Meanwhile, Zafiryadis et al. extensively discussed the fundamentals of a coarse-graining technique, specifically with DEM-based simulations of fluidized beds [32]. The article provided a comprehensive overview of these concepts. It was demonstrated that the coarse-graining method shows promise in addressing the overwhelming computational demands associated with DEM simulations of fluidization units at pilot and industrial scales. The article breaks down and examines the key components of the coarse-graining method and explores how its simplification affects the amount of computational resources saved. The study also considers both the current trends and future developments in this field.

Another study was conducted by Zhao et al., which primarily focused on the flow of gas and solid materials at high temperatures to enhance heat and mass transfer processes [33]. Computational fluid dynamics and Lagrangian tracking were employed for this investigation. The study focused on characterizing particle dynamics, residence times, and the resulting transfer processes under pulsating conditions.

Moreover, Eulerian–Eulerian simulations were utilized to comprehensively study the gas–solid flow in a fluidized bed as opposed to the gas jet mill by Li et al. [34]. The analysis involved examining time-averaged volume fraction, velocity, and two-phase flow fields to understand the mill's operation better. The impact of particle-flow dynamics, arising from various combinations of solid hold-up and nozzle air velocity, was evaluated regarding milling performance characteristics.

Zhang et al. employed commercially available software to explore the movement of a gas–solid mixture in both the riser and downer sections of a circulating fluidized bed (CFB) cold-flow model [35]. The study investigated solids' residence time, hold-up, and radial velocity profiles to determine the likelihood of back mixing and flow nonuniformity.

The study of [36] employed macroscopic modeling to forecast the efficacy of vibrated fluidized bed dryers across diverse situations. This demonstrated the enormous advances flow sheeting simulators have made in portraying complicated fluidized bed process units. Specifically, an open-source framework called Dyssol was used to construct and test a continuous dryer model.

In 2017, a CFD-DEM simulation was carried out to study the mass transfer mechanism under riser flow conditions. It was revealed that gas bypassing is enhanced by clusters, which result in poor gas–solid contact. It was revealed that CFD-DEM is an effective tool in predicting the performance of the particle clusters [37]. CFD-DEM was used to demonstrate the fluidization process of cylinder-like particles using various formations and numbers of spheres in a fluidized bed, and it was found that Cyl-60 and Cyl-19 agree more with experimental data compared to Cyl-5 and Cyl-7. It was revealed that particles prefer to be positioned horizontally in the fluidized bed and that particles in the vertical position increase in number as they approach the walls [38]. Another numerical method, the virtual dual-grid (VDGM), was proposed by a team of researchers observing the behavior of particle fluidization with complex geometry. The CFD-DEM-VDGM model was implemented to simulate the behavior of particle fluidization in a coating furnace at high temperatures at an industrial scale [39] and was able to model the dynamics of corn-shaped particles in a fluidized bed [40].

Aside from CFD-DEM, another modeling and simulation technique is called the Multiphase Particle in Cell (MP-PIC); the difference between DEM and MP-PIC is that while DEM calculates the particle interaction from particle collision, requiring the exact location of each particle, MP-PIC tracks a group of particles that are of the same property, such as size, density, etc., and the solid stress term is used to calculate particle interaction. This enables the possibility of simulating reactors of a larger scale of up to 10^{16} while also being able to model the particle size distribution [41]. Another study focused on developing and applying a scaling law to enhance the multiphase particle-in-cell (MP-PIC) method for simulating fluidized beds. The researchers analyzed the scaling law and then used it to scale the MP-PIC approach. Two fluidized beds were simulated to validate the effectiveness of the scaled MP-PIC method. The results demonstrated that the scaled MP-PIC approach significantly reduced solids' volume fraction errors and velocity distribution across a wide range of coarse-graining ratios for the simulated conditions. In the future, the researchers aim to develop a scaling law that considers the variety within a numerical particle, which is anticipated to further enhance the performance of coarse-grained modeling in fluidized bed simulations [42].

As previously mentioned, another numerical method is the PBM. Various studies explored the use of this simulation model. Some reports are as follows: the employment of the Eulerian–Eulerian method and the population balance model (PBM) to account for bubble aggregation and fragmentation, enhancing the accuracy of predicting bubble size distribution and phase hold-up. The simulation results revealed variations in fluid analysis and gas dispersion characteristics in the stirred tank at different rotational speeds. As the rotational speed increased, there was a noticeable increase in the presence of small-diameter bubbles, concentrated primarily in areas with higher fluid velocities. The higher the rotational speed, the greater the proportion of small-diameter bubbles, while the impact on the content of large-diameter bubbles was relatively minimal [43].

The last modeling and simulation to be discussed is the LBM or Lattice Boltzmann method. A few studies considering this investigated the process of two-particle sedimentation. The Lattice Boltzmann method was utilized to simulate fluid flow, while the DEM was employed to simulate the dynamics of particles. An immersed boundary method was incorporated to handle the interactions between particles and the fluid. By employing the IBM-LBM-DEM approach, the collision process of particles in the fluid and between the rigid walls was calculated efficiently and accurately, capturing information about the particles and the flow field. Simulations of settling a single 3D particle were conducted to validate the numerical method used [44].

5. Particle Fluidization and Its Applications

The utilization of particle fluidization is crucial in various industrial procedures owing to its broad spectrum of cutting-edge experimental assessments and characterization techniques, inventive operational blueprints, and original applications like fluidized bed coating. Much attention has recently been focused on fine particles among the various particulate materials. A diverse range of industrial domains is expected to harness ultrafine particles to leverage their distinct attributes and novel functionalities.

Electroplating, chemical vapor deposition, and physical vapor deposition are just a few technologies used to create fine particles, which have widespread applications across various industries. Most fluidized bed coating operations in the food and pharmaceutical industries use core particles with a diameter greater than 200 m to prevent the formation of agglomerates [35].

A large amount of intricacy is involved whenever a coating layer is applied to the surface of a particle [36]. Most commonly, a solution is sprayed over the particles, and then the liquid film completely covers every one of the particles. The coating of the particles occurs due to the formation of new solid layers due to the evaporation of the liquid in the film. The process might begin with the formation of droplets, followed by wetting and drying [37]. However, this may vary based on the apparatus used and the coating material's circumstances.

The fluidization process is an important method in particle formation because it offers several benefits, including high rates of heat and mass transfer and effective mixing and homogeneity. Due to recent advancements in experimental methods and mathematical models, the spray-fluidized bed coating of particulate materials has gained recognition as an industrial process [38,39]. However, particles larger than 100 m are typically the smallest for which a fluidized bed coating may be accomplished without severe agglomeration. In contrast, conventional two-fluid nozzles form a spray comprising droplets with an average diameter of 40 μm or greater [40]. This size range can be classified as relatively large in relation to particle dimensions.

In spray fluidized bed (SFB) coating, it is common for the thickness of the former to exceed 30 μm and often surpass it significantly. This phenomenon can be attributed to the large size of the droplets present in the respective sprays. It is common for the mean diameter of droplets to be 40 μm [38]. However, it is not uncommon for two fluid or pressure nozzles to create droplets with significantly larger diameters. Alternate atomizers, such as those used in ink-jet printing nozzles, may be able to reduce droplet size a certain amount; however, atomizers exhibit certain limitations regarding their ability to effectively process liquids that contain high levels of solids and their overall throughput capacity.

Conventional techniques can be enhanced by refining particles or altering the fluidized bed to address these challenges. The granulation of powders into larger particles is a viable method for enhancing the fluidization, drying, and coating procedures within a fluidized bed [41]. In addition, most support strategies call for complex modifications to the conventional fluidized bed arrangement, which may require significant additional expenses.

Coating fine particles has been attempted recently by multiple researchers utilizing a variety of equipment and experimental parameters. Fluidized bed coating is a complex process in striking the optimal balance between mixing, wetting, and drying [42–45]. Factors, such as air temperature, flow rate, and coating solution, greatly influence the product's quality. Over the past few years, extensive experimental and numerical research for huge particles covered in fluidized beds utilizing typical nozzles has been carried out to understand the effect of these variables.

Prior studies have indicated that elevating the inlet air temperature facilitates the desiccation of moist particles in the coating procedure. Furthermore, the velocity at which the coating solution flows directly correlates with the coating layer's magnitude. Although a plethora of studies are available on the coating of particles with a diameter greater than 200 m, the investigation of the coating properties of fine particles has been comparatively neglected.

Hampel et al. [46] conducted a recent study that led to the creation of a novel technique that integrates spray drying and coating processes for particle formation. The proposed methodology involved the application of a coating solution onto the targeted fine particles through a dual-fluid nozzle. The goal was to create droplets containing exactly one particle as they exited the nozzle. Following the evaporation of the water contained within the droplet, a minuscule layer of solid film was formed on the particle's surface. This cutting-edge, budget-friendly, and straightforward technology might, to a certain extent, prevent agglomeration; nevertheless, partially coated or uncoated products would still be produced under certain process conditions.

This study presents a significant shift from the traditional use of spray to the use of aerosol as a coating technique in fluidized beds. For the aerosol, produced using a process that had only recently been devised [47,48], the Wurster fluidized bed was charged with the material through the lower section of the chamber. It was recently demonstrated [49] that such an aerosol may easily build an ultrathin coating on big particles in a conventional fluidized bed. In this case, the focus was on the coating of small particles. The underlying assumption was that aerosols measuring fine particles are better serviced by sprays 10–100-times smaller than conventional sprays since this enables homogeneous coating layers without the problem of severe agglomeration seen in conventional spray fluidized bed particle-coating systems. This would hold, provided aerosols with dimensions 10–100-times smaller than conventional sprays could be generated.

The study of Zhang et al. [35] makes a valuable contribution toward advancing a novel coating methodology for fine particles with a diameter of approximately 50 μm. The simultaneous use of a Wurster fluidized bed and a cutting-edge aerosol atomizer is responsible for the novelty of this method. The study investigated the impact of core materials, coating solutions, and operational parameters on the quality of the coating and the yield of the process. The Wurster fluidized bed can coat fine particles without inducing agglomeration by utilizing exceedingly minute aerosol droplets.

This revolutionary technology could help the pharmaceutical, food, catalytic, and other sectors create novel products using coated small particles. The experiments' results indicate that the coating layer's quality degraded as the coating solution viscosity decreased. On the other hand, it was discovered that maintaining a moderate process temperature improved the creation of the coating layer and its overall quality. It was also discovered that reducing the amount of aerosol fed into the process helps enhance its overall production.

The aforementioned novel methodologies possess the potential to pique the interest of various industries, such as pharmaceuticals, food, catalysts, and others. These approaches may aid in the creation of novel products that rely on coated fine particles.

6. Process Intensification and Sustainability in Particle Fluidization

Particle fluidization exhibits significant potential concerning process intensification and sustainability. It is an innovative technique that involves the suspension of solid particles in a fluid medium, creating a dynamic state where the particles exhibit fluid-like behavior. Taking advantage of the unique properties of fluidization is a promising approach to improving industrial processes, leading to increased efficiency, reduced energy consumption, and minimized environmental impact. Moreover, manipulating particle–fluid systems provides avenues for optimizing chemical reactions, enhancing mass and heat transfer, improving separation processes, and developing innovative technologies across various fields. The sustainable nature of particle fluidization, which offers an opportunity to use renewable resources and reduce waste generation, renders it a compelling path toward achieving environmentally friendly and economically viable solutions.

6.1. Process Intensification

Due to its numerous advantages, particle fluidization has been widely recognized as crucial in diverse industrial processes and process intensification. One of the significant advantages is enhanced heat and mass transfer [4]. The fluidization process enhances inter-particle interaction with the fluid medium, achieved by the passage of gas or liquid through a bed of solid particles. This phenomenon has been observed to facilitate heat and mass transfer efficiently. The optimization of heat and mass transfer is critical in processes, such as drying, combustion, and gasification, where the efficient transfer of heat and mass is critical for achieving optimal performance. A study investigated the drying process of biomass materials in a fluidized bed by employing a pulsating gas flow. They found that pulsated fluidized beds can be operated at velocities lower than the minimum fluidization velocity while ensuring sufficient heat and mass transfer rates for effective drying, reducing the requirement for drying resources. In a typical situation where the average gas velocity is higher than the fluidization velocity, as in (a), both pulsation frequencies can fluidize for a sufficient time, although a high frequency would give better results. However, when the gas velocity is lower than the fluidization velocity, as shown in (b), a low pulsation frequency can also produce an acceptable area of fluidized zones. Fluidization is crucial in drying biomass as it determines heat and mass transfer rates and temperature distribution [4].

Particle fluidization is a favorable method for providing optimal solid–gas interaction. This is particularly beneficial for solid–gas reactions, including but not limited to adsorption or desorption. The use of fluidized beds has been shown to enhance reaction kinetics and increase reaction rates due to the augmented surface area and improved particle mixing. In a study [50], the researchers compared a fixed and fluidized bed setup for volatile organic compound (VOC) adsorption. The results showed lower heel buildup in a fluidized bed. Heel buildup refers to the adsorbate accumulation that cannot be removed from the adsorbent, which was found to influence mass transfer due to improved gas–particle contact.

Furthermore, fluidized bed processes offer scalability and flexibility, allowing easy adjustment of the production capacities and handling different particle sizes and types. These advantages make particle fluidization a valuable technique in industrial applications, such as granulation, coating, chemical reactions, and environmental remediation. The authors of [51] showed an alternative, simple, low-cost, and scalable method for synthesizing silicon monoxide (SiO) electrodes. It uses fluidization thermal chemical vapor deposition (FTCVD) in a fluidized bed to prepare SiO for carbon coating that inhibits aggregation while improving dispersion performance when used in a battery.

6.2. Sustainability

Particle fluidization demonstrates significant potential in terms of sustainability that aligns with the principles of green and sustainable practices. One notable aspect is its energy efficiency. Due to their enhanced heat and mass transfer capabilities, fluidized bed systems often require lower energy inputs than traditional processes. This efficiency reduces energy consumption and lowers carbon emissions [4,52]. The drying kinetics of paddy through ultrasound-assisted fluidized bed drying were examined in [52] and were determined to decrease the specific energy consumption by approximately 22%.

Additionally, it offers opportunities for operations that are more ecologically sound. For instance, in fluidized bed combustion, uniform mixing and efficient burning of fuel particles reduce nitrogen oxide and sulfur dioxide emissions. The authors of [53] reported a significant decrease in CO and NOx emissions in the fluidized bed combustion of biomass with the help of oxy-fuel oxidants. The decrease in NOx emissions can be attributed to two factors: first, the increase in bed temperature leads to the release of more volatile-N, which is subsequently converted in the dense bed zone; second, the lower dilution of gases within the dense bed zone results in a higher concentration of CO in this region, thereby facilitating the reduction of NOx.

The adaptability of fluidized beds in accommodating diverse materials, such as biomass and waste streams, presents opportunities for implementing sustainable waste management practices and circular economy principles. Several studies have investigated the potential of various biomasses and their applications in fluidization. The authors of [4] focused on the performance of Douglas fir and pine sawdust in a pulsed fluidized bed with vibration. The combustion of biomass, specifically non-woody fuels, woody fuels, and distilled spirit lees, has also been examined [53,54]. The application of biomass in particle fluidization is widely researched in light of the growing demand for sustainable and renewable resources.

Lastly, particle fluidization provides opportunities for process intensification, resulting in smaller equipment sizes, a reduced carbon footprint, and lower capital investment [4,52–54]. This aspect supports the sustainable use of space and resources in industrial applications [51,55,56] and has also proved the scalability of fluidization processes.

7. Machine Learning and AI in Particle Fluidization

Particle fluidization is one of several industries where machine learning and artificial intelligence have found use. The operating conditions of fluidized bed reactors or other particle fluidization systems can be optimized using machine learning (ML) methods. The best settings to accomplish the desired results, such as increased efficiency or decreased energy consumption, may be suggested by ML models by gathering real-time data on factors, such as particle size, fluid velocity, and temperature.

AI-driven simulations can provide insight into complex particle–fluid interactions in fluidized beds. These simulations can aid scientists and engineers in comprehending how various factors impact particle behavior, allowing them to create systems that are more effective. For example, in a study by Xie et al., a data-driven model was developed using a two-level optimization algorithm, allowing for the automatic discovery of a correlation for the bed expansion ratio from experimental data. This data-driven modeling approach offered the advantage of directly identifying the most influential groups of dimensionless parameters, thereby leading to a more accurate correlation [57].

The mobility of specific particles inside a fluidized bed may be tracked using ML algorithms. Li et al. trained a machine learning model for pixel-wise classification and applied it to acquire wood and LDPE particle masks for particle image velocimetry and particle-tracking velocimetry processing, respectively. The influence of wood particles on factors, such as slugging frequency, mean and variation of bed height, and characteristics of particle velocities/orientations, was measured and compared. Their findings revealed substantial disparities in fluidization behavior between cases involving only LDPE particles and cases of binary fluidization [58]. Understanding particle behavior, segregation, and mixing may be gained from this knowledge, which is important for increasing process effectiveness.

Advanced control techniques for preserving stable fluidization conditions may be created using ML algorithms. These techniques might vary in real time in response to modifications in flow rates, feedstock composition, and other factors. A fuzzy adaptive PID controller founded on the decoupling principle was employed by Chen et al. to enhance the control performance of the biomass circulating fluidized bed in the face of load fluctuations. The resulting controller has the capability to effectively decouple the boiler bed temperature from the main steam pressure throughout the combustion process. Moreover, the controller markedly enhances the resistance to external disturbances and stabilizes the control loops for the bed temperature and main steam pressure, as substantiated by the simulation outcomes [59].

Through the analysis of data from sensors tracking the fluidization process, AI may assist in forecasting maintenance requirements. By examining sensor data, AI-powered systems may identify abnormal circumstances or deviations in particle fluidization processes. These technologies can then identify the underlying causes of the problems and recommend solutions. The technology can warn operators of possible problems before they result in equipment failure or downtime by spotting trends and abnormalities. Yadong et al. [60]

presented a defect diagnostic approach for complicated chemical processes based on multi-model fusion. Training a very deep factor decomposer diagnostic model to extract and fuse linear, low-order interaction and high-order interaction features in an all-around manner to adaptively establish the correlation between fault features and fault conditions improves model memory and generalization capability. Using the Tennessee Eastman Process dataset and the Fluidized Catalytic Cracker fractionation unit dataset, the findings revealed that the proposed technique outperforms existing diagnostic tools in accuracy and recall metrics.

AI can also help with the design of innovative fluidized bed systems by taking into account many variables and limitations at the same time. This can result in more creative and efficient designs. For example, Cui et al. [61] proposed a scale-up prediction model based on an adaptive particle swarm optimization support vector machine (APSO-SVM) for the combustion characteristics of an S-CO_2 CFB boiler. Their method effectively predicts the boiler in the scaling process from the standpoint of boiler capacity, optimizes the scale-up regularity expression through numerical simulations, greatly reduces the time, cost, and applicability of enlarged design by modifying complex numerical simulations, and lays the foundation for S-CO_2 CFB boiler application in the industrial field with acceptable operation accuracy.

It is essential to highlight that successful ML and AI applications in particle fluidization need high-quality data gathering, preprocessing, and model training. Furthermore, domain knowledge is required to comprehend the data and make educated decisions based on the AI-generated insights.

8. Research Gaps

It is widely recognized that applications of the fluidization technique may be found in various research and manufacturing processes, but these applications are by no means complete. As just mentioned, this is noteworthy in terms of the variety of subject areas covered and the quality of the various contributions made. There has been a consistent introduction of new configurations and cleaner solutions for increased performance and sustainability throughout the years, such as in the efficient use of clean and renewable energy sources; nonetheless, the available utilizations have not even come close to being exhausted. This technology's effectiveness in fluid–solid contact, enhanced heat/mass transfer, and superior solids mixing is the foundation of its widespread adoption since they guarantee high performance and operational flexibility. In addition to the ongoing difficulties associated with integrating environmentally friendly technologies and processes, a significant amount of ground still has to be covered through additional research and development.

Despite significant progress in particle fluidization, several challenges and limitations persist. Understanding and controlling complex hydrodynamics, particle mixing, and segregation phenomena in large-scale systems remain poorly understood. Developing accurate and computationally efficient models that capture the behavior of cohesive and non-spherical particles is another challenge in CFD. Addressing the challenges associated with particle attrition, accumulation, and elutriation, which can affect process efficiency and product quality, is still challenging. The influence of process variables, such as particle size distribution, fluid properties, and operating conditions, on the performance and stability of fluidized bed systems needs to be studied in detail. Moreover, ensuring the reliability and scalability of experimental and computational methodologies to bridge the gap between lab-scale studies and industrial applications is crucial.

Fluidized beds are superior to other fluid–solid contactors in performance due to their enhanced efficiency and increased fluid–particle interaction. The agitation of the particle phase in fluidized beds has been observed to enhance transfer coefficients for hydrodynamics, heat transfer, and mass transfer. The bed exhibits a lower pressure drop compared to permanent beds. The mitigation or elimination of dead zones, hot patches, inhomogeneities, and disparities in product quality is achieved. Notwithstanding its potential, the complex interplay between fluid and solid flow fields and other associated challenges impedes the complete utilization of fluid–solid processing technology. Research on the scale-up and optimization of fluidized beds has persisted for several decades since its inception. These endeavors aim to achieve a fundamental comprehension.

9. Future Outlook

Particle fluidization is a highly versatile process with numerous industrial and economical applications. It can potentially revolutionize energy production, fuel conversion, and other fields, such as mineral processing, food engineering, and pharmaceutical manufacturing. Moreover, it can be integrated into other emerging technology, leading to compact and efficient processes. Over the years, there has been a continuous introduction of new configurations and greener solutions aimed at enhancing performance and sustainability. For instance, there has been an increased focus on making effective use of energy sources that are both environmentally friendly and renewable. Despite this, there is an opportunity for more investigation into how these solutions could be used. The efficacy of this technology is rooted in its ability to facilitate fluid–solid interaction, optimize heat and mass transfer, and promote thorough mixing of solids, thereby ensuring superior performance and operational versatility. Apart from the persistent obstacles in pursuing environmentally sustainable technologies and process integration, numerous areas still necessitate additional research and development.

Particle fluidization is a fundamental process, extensively employed in various industries, including chemical engineering, pharmaceuticals, energy, and environmental sciences. It involves the suspension and transport of solid particles in a fluid medium, exhibiting complex behaviors and interactions. As researchers in this field, it is crucial to explore and discuss the identification of future research directions, emerging trends, and the challenges and limitations that must be addressed. This discussion aims to shed light on the key aspects and potential avenues for further investigation in particle fluidization.

One crucial research direction is the development of advanced characterization techniques to gain a deeper understanding of the fluidization process. High-resolution imaging techniques, such as X-ray computed tomography (CT), positron emission particle tracking (PEPT), and magnetic resonance imaging (MRI), provide valuable insights into the dynamics of particle–fluid systems. Using these techniques to investigate hydrodynamics, particle–particle interactions, and heat transfer mechanisms can enhance our understanding of fluidization phenomena and guide the design of optimized systems.

Another significant research direction is the advancement of multiphase flow modeling and simulation approaches. Computational Fluid Dynamics (CFD) combined with the Discrete Element Method (DEM) or Eulerian–Eulerian modeling can simulate complex phenomena occurring in particle fluidization systems. Developing accurate and efficient models incorporating particle–particle and particle–fluid interactions, turbulence, and multiphase flow behavior will allow for better prediction and optimization of industrial fluidized bed processes.

Exploring novel particle materials and their applications in fluidized bed systems is an emerging trend. Research can focus on using nanoparticles, granules, or functionalized particles to enhance heat and mass transfer, improve reaction kinetics, or achieve specific separation processes. Investigating the properties and behavior of such advanced particles in fluidization systems could lead to the development of more efficient and sustainable processes in industries, such as catalysis, pharmaceuticals, and energy production.

More thorough and real-time monitoring of particle–fluid interactions will be possible as sensor technology and data-gathering methods advance. This flood of data will feed the development of powerful machine learning models capable of properly predicting and controlling fluidization behavior. AI-powered simulations will improve in accuracy and precision, allowing them to simulate large-scale systems for the first time. ML algorithms may help identify complicated patterns and correlations within particle–fluid systems, resulting in optimal process parameters, lower energy usage, and higher product quality.

Predictive maintenance based on artificial intelligence will become a fundamental element of particle fluidization processes, saving downtime and lowering maintenance costs.

Efforts should be directed toward the process intensification and scale-up of fluidized bed systems. Developing innovative reactor designs, such as microreactors, structured catalysts, or hybrid systems, can enhance process performance, reduce energy consumption, and optimize product yields. Additionally, investigating the challenges associated with scaling-up fluidized bed processes while maintaining their efficiency and stability will be crucial for industrial implementation.

Addressing the challenges and limitations of particle fluidization from an environmental and sustainability standpoint is of the utmost importance. Research can focus on reducing emissions, minimizing energy consumption, and optimizing resource utilization in fluidized bed processes. Investigating the potential of renewable energy sources, waste valorization, and carbon capture technologies within fluidized bed systems can contribute to a greener and more sustainable future.

Author Contributions: Conceptualization, E.C.R.L.; writing—original draft preparation, J.B., D.A.T.F., V.G.M., V.R. and L.J.T.; writing—review and editing, E.C.R.L.; supervision, E.C.R.L.; project administration, E.C.R.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

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