

Review

Review of Experimental Activities and Recent Developments of Spouted Bed Reactors at Different Operational Scales

Valerio Carozzo, Elisabetta Arato  and Cristina Moliner * 

Dipartimento di Ingegneria Civile, Chimica e Ambientale (DICCA), Università degli Studi di Genova, Via Opera Pia 15, 16145 Genova, Italy; valerio.carozzo@edu.unige.it (V.C.); elisabetta.arato@unige.it (E.A.)

* Correspondence: cristina.moliner@unige.it

Abstract: Recent research advances and technological developments of spouted bed reactors (SBRs) have been discussed in this work. SBR has aroused increasing interest since their invention in 1955 due to its flexibility in processing different feedstocks and the high process yields that can be achieved due to its characteristic fluid dynamics. However, even though highly satisfactory results have been obtained at the laboratory scale for different applications (i.e., drying or thermochemical reactions, among others), their full implementation at an industrial level is still scarce, mainly due to the challenges encountered for their scale-up. In this work, an initial short description of SBR and configurations is followed by a review of the main experimental activities that have been conducted at different scales in the period 2013–2023. Advanced solutions such as multi-unit reactors and the use of rectangular geometries instead of the classical cylindrical ones have arisen as potential areas for further study and development to achieve a reliable implementation of the spouted bed technology at an industrial scale.

Keywords: spouted bed; novel technologies; scale-up; experimental activities; laboratory scale; industrial scale



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1. Introduction

Spouted bed reactors (SBR) stand out as a promising technology for many applications such as drying, coating, desulphurisation or thermo-chemical reactions, among others. SBR can be described as a conventional fluidisation reactor where the inlet is composed of a single orifice, instead of the distributor plate of traditional fluidised reactors (FBR), promoting an enhanced recirculation of solids with a particular multiphase pattern [1]. Due to their characteristic dynamic behaviour, the fluidisation regime differs from FBR. Two different regions can be identified in FBR: the bubble phase and the emulsion phase; while three different regions are observed in SBR: spout, fountain and annulus (Figure 1a). Figure 1b shows the development of the spouting regime, from the initial fixed bed of particles (a mixture of straw and PET) to the final creation of the fountain. Air is fed at the bottom of the reactor creating a channel through the bed of particles, the spout, above the inlet and at the centre of the bed [2]. The annulus is formed by the solids between the wall and the spout behaving as a packed bed. The solid particles move upward until they reach a certain height where they start to lose velocity and fall, creating the fountain [3,4].

The described fluid dynamic behaviour provides SBR with technological advantages with respect to other types of reactors dealing with solid particles such as FBR or mechanical stirrers. The single central nozzle coupled with the base angle from 35 to 60° guarantees a high mixing yield without the formation of dead zone or particle segregation. Thanks to this vigorous mixing, high efficiencies are achieved when working with coarse particles with different diameters and densities, also reducing the necessity of pre-treatment of the feedstock [2].

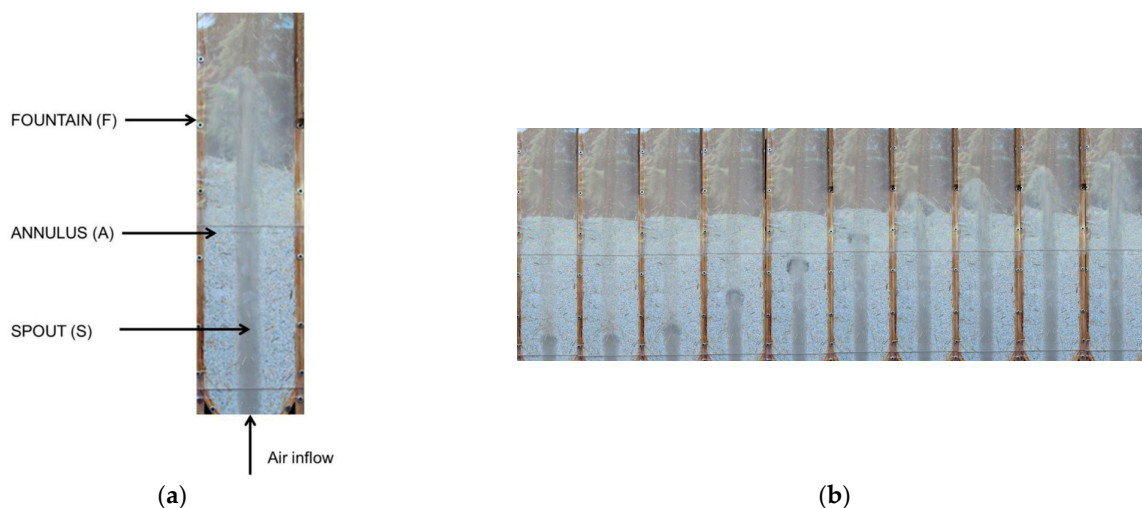


Figure 1. (a) Regions in the SBR [5]; (b) evolution of the spouting flow regime [5].

Furthermore, the energy needed for stable operation is lower compared to conventional reactors (like the stirrer of a fluidised bed reactor) due to the lower pressure drop across the bed of particles, making SBR an interesting technology in many applications, such as drying, coating, desulphurisation and thermochemical process [6,7]. Better mass and heat transfer rates are achieved because of the enhanced solids mixing, improving the efficiency of the processes. In summary, and compared to FBR, SBRs are more flexible, can treat physically different particles in a more efficient way and the energy required in the plant is lower [8].

However, despite the SBR's great potential, its use at an industrial level is still scarce. So far, spouted beds have been mainly studied at the laboratory scale, with the main focus on identifying the best working conditions for each specific application and, once established, ascertaining the best configuration for their possible scale-up [9]. Table 1 shows the number of reviewed papers for this work, in the range of time between 2013 and 2023, at the different operational scales. The scale of the reactor was defined by the quantity of feedstock treated on a daily basis, closely related to the dimensions of the reactor. Laboratory scale works were considered for inlet flows below 10 kg/d whereas demonstration scale units reached up to 100 kg/d. Industrial plants worked, on average, with flows around 480 kg/d. Lab scale publications accounted for 83 of the total 96 works, which highlights the very low quantity of studies dealing with scaled-up technology, even during the most recent years. As discussed in one of our previous works [5], simulation studies could provide useful insights into the specific behaviour of these reactors and could help in designing their best configuration and mode of operation. For that reason, work on the simulation of industrial-scale units will be also discussed (Section 3.2).

In this framework, the main objective of the present work is to define the updated state of the art of systems based on spouted bed reactors highlighting their main scientific advances, their current applications and process efficiencies, and their state of implementation at the different scales (lab, demonstration and industrial). To achieve this goal, the most representative experimental works on SBR (mainly in laboratory scale) of the period 2013–2023 have been analysed. In addition, the second aim was to identify the scientific gaps for their successful implementation at larger scales and to propose further areas of research that could help in surpassing these gaps and technological barriers. With this purpose, Section 2 will describe the important features of SBR, from their configuration to its fluid dynamic description, key for their efficient application. Section 3 will review the different reactors developed in the last decade for each application and finally, Section 4 will draw some conclusions on the current research developments, the degree of implementation and the limitations that need to be overcome to achieve a full and reliable technology at the industrial level.

Table 1. Number of reviewed papers at lab, demonstration and industrial scale.

Years	Lab Scale	Demonstration	Plant/Industrial-Scale
2013	10	-	1
2014	10	1	-
2015	12	-	1
2016	14	-	-
2017	4	-	-
2018	7	-	-
2019	5	-	1
2020	3	1	-
2021	3	1	-
2022	2	1	1
2023	13	5	-
TOTAL	83	9	4

2. SBR Description and Different Configurations

SBRs are highly sensitive to both the geometry of the spouted bed unit and the physical properties of the inlet solids. One of the design steps that will define the success of these reactors is the delimitation of the operating conditions that allow a stable spouting regime. For that reason, the initial characterisation of their fluid dynamic behaviour becomes a key step in their development. The initial design parameters for an SBR are based on: (i) structural (diameter of the nozzle (D_i) and the diameter of the reactor (D_c), the angle of the base of the reactor (γ)) and (ii) hydrodynamic variables (minimum spouting and onset velocity (U_{ms}), dimension and shape of processed solids, maximum and constant pressure drop (ΔP_{max} and ΔP_{stable}), maximum spouting height (H_{max})). Typical column diameters (D_c) are between 80 and 200 mm and should not exceed 12 times the size of the gas inlet to avoid instabilities and the base angle (γ) should lie in the range of 35–60°. Due to their functioning, the high velocity of the inflow air entering from the bottom of the SBR enhances the mixing degree inside the bed and the gas–solid contact. At stable conditions, the fluidisation velocity, called minimum spouting velocity, is lower than the velocity needed in traditional fluidised reactors [1], which results in a reduction in the pressure drop of the system and, consequently, in its energy requirements.

In general, SBRs can be classified according to their geometry in cylindrical, conical and rectangular reactors (Figure 2).

- Cylindrical spouted beds. They were first proposed by Mathur and Gishler [10]. They have a cylindrical bed shape and can be easily constructed. Their main disadvantage, the appearance of dead zones at the bed corners where particles do not take part in the circulation of solids, and the maximum bed height that can be processed, limit their application in a wide range of processes.
- Conical spouted beds. First proposed by Mujumdar [11], they consist of a conical bottom and a cylindrical top. Their main characteristic is the minimisation of dead zones, in contrast with cylindrical reactors. Thanks to its geometry, conical bed shapes highly promote the mixing of solids and gas–solid contact greatly increasing process efficiencies. However, these types of reactors are more sensitive to geometric and operational parameters, making the delimitation of the stable conditions more difficult [12].
- Rectangular/square spouted beds. It represents the most interesting technology for a further industrial scale-up as the width of the rectangular base can be easily increased using equivalent fluid dynamic correlations [13]. Also, stagnant or dead zones in the annulus are greatly minimised improving solids mixing and mass and transfer rates.

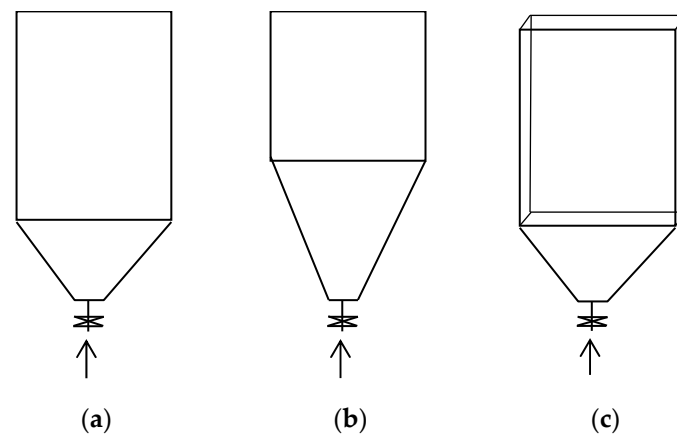


Figure 2. Configurations of SBR: (a) cylindrical, (b) conical and (c) rectangular. Conical reactors present a more pronounced basis with a smaller cylindrical part above, compared to cylindrical spouted bed reactors.

Many researchers have also studied the use of internal devices inside the reactor, such as draft tubes (porous or not), draft plates, fountain confiners or multi-jet inlets with the purpose of increasing process efficiencies. Draft tubes (Figure 3a) and draft plates are devices vertically placed a few centimetres above the air inlet. Their main aim is to create a “forced” channel for air to go through the bed of particles. As a result, more controlled solid circulation rates and residence times are obtained. An important parameter to take into account when designing these devices is the ratio H_d/H , with H_d being the gap from the base to the bottom location of the draft tube (Figure 3a). The fountain confiner has the purpose of widening the operational range up to four times with respect to conventional SB. For example, it is proven to increase the ratio between the inlet diameter and the particle diameter from 20 to 30 (conventional ratio) to 1000 [14]. The multi-jet inlet or secondary fluidisation system (flow of air coming from the side of the bed, Figure 3b) has the purpose of enhancing the air circulation inside the reactor and preventing the formation of dead zones. The mixing degree is improved and, consequently, the gas–solid contact [15]. These devices represent an interesting technology to enhance efficiencies, but they can increase the costs and the maintenance of the reactor, as there are more risks of clogging and erosion of the material.

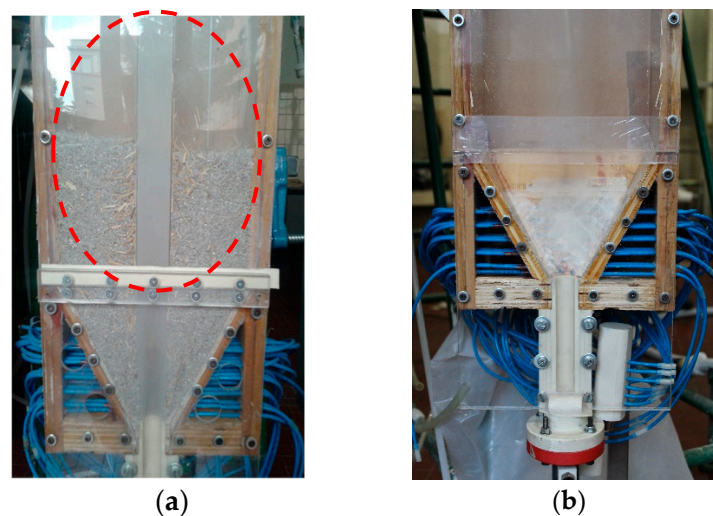


Figure 3. SBR with a draft tube (a) and secondary fluidisation system (b).

3. Experimental Applications

SBRs have been studied for different applications such as drying, coating, desulphurisation, and thermochemical reactions. Numerous experimental research has been carried out since their invention in 1955 mainly from two different, and complementary, points of view:

1. The so-called “cold-flow tests”, normally at room temperature, aimed at studying the geometric parameters of the reactors and their different possible configurations. This fluid dynamic characterisation is essential to establish adequate operational parameters (spouting velocity, use of auxiliary devices, . . .) to ensure a stable spouting regime.
2. Study of the process variables in the different applications (quantity of materials, temperature, pressure, . . .) to optimise process efficiencies.

As highlighted in Section 1, these latter studies have been mainly carried out at a laboratory scale since they are simpler to modify and control the operating conditions. For this work, a deep review of the experimental activities related to process optimisation has been carried out. In particular, Section 3.1 is devoted to the review of all experimental works related to drying (Section 3.1.1), coating (Section 3.1.2), desulphurisation (Section 3.1.3) and thermochemical reactions (Section 3.1.4). Successively, Section 3.2 describes the demonstration and industrial-scale plants already developed in the last 10 years.

3.1. Lab-Scale Reactors

Figure 4 shows the number of reviewed publications in the period 2013–2023. Thermochemical processes can be identified as the most applied technology for all the years of study, followed by drying, particularly during the first years while coating remains at low numbers in the whole time range. Also, a gap in publications in 2020 and 2021 due to the COVID-19 situation can be noticed and fully overcome in 2023.

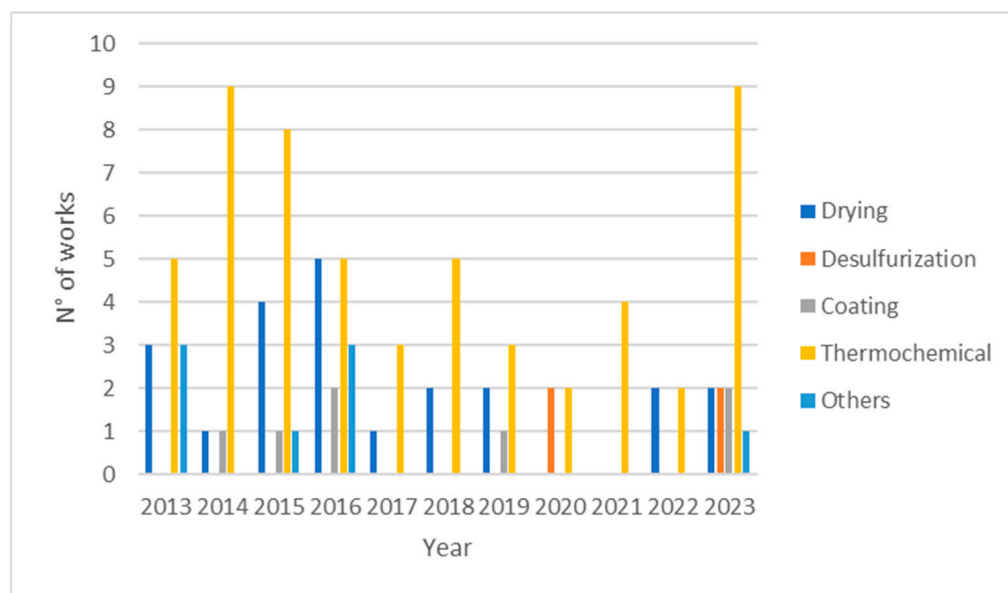


Figure 4. Number of works on different processes in the last years.

In general, the process diagram for all applications based on SBR is shown in Figure 5.

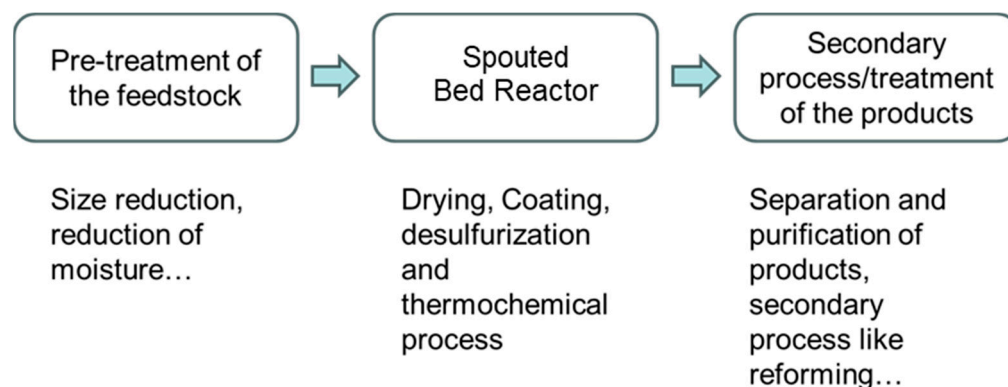


Figure 5. Process flow diagram with the main unit operations for processes conducted with SBR.

3.1.1. Drying

SBRs have been widely used for the drying of seeds and food since their very first development by Mathur and Gishler in 1955 [10]. Conventional drying presents difficulties in treating coarse particles, which increases the risk of particle segregation. This can result in non-homogenous heat transfer rates that could decrease the quality of the dried product. SBRs were first studied and used to avoid these problems as they can overcome the difficult traditional fluidisation of coarse particles. SBR can work at a wide range of particle diameters without fluidisation problems such as low mixing degree, segregation and stratification. A better gas–solid contact also helps the reduction in the necessary temperature for drying, especially important when the treated solid is sensitive to it. To sum up, SBR can ensure a good drying performance and uniformity of products, with reduced costs of operation compared to FBR.

Lots of works have dealt with the drying of seeds, food or powder as described in the next paragraphs. Camu camu pulp was dried in a cylindrical spouted bed reactor to study the difference between this process and a freeze-drying one. The process was carried out with 2.5 kg of HDPE as inert material and different concentrations of maltodextrin (0%, 3%, 6%). The properties of camu camu were similar for both processes, and the temperature reached inside the SBR caused a decrease in antioxidants [16].

The application of microwave energy for drying coffee beans in a glass conical spouted bed reactor was studied by Jindarat and colleagues [17]. The process was performed at 50, 60 and 70 °C, with 200 g of wet coffee beans, and the test ran until the moisture of the coffee beans reached 10 wt%. (dry basis). The study showed a higher quality of the product (in terms of flavour, colour and taste) using SBR compared to a conventional process, while costs were reduced.

As discussed before, SBR can work at lower temperatures compared to conventional reactors. In this way, it is possible to treat biomass that degrades at high temperatures or with high residence time. Costa and collaborators [18] used a cone–cylindrical spouted bed reactor for drying açai powder without losing its properties. Tests were conducted at 105 °C, the temperature needed for reducing the moisture from $83.82 \pm 0.04 \text{ g } 100 \text{ g}^{-1}$ to a range from 3.22 to 5.40 g 100 g⁻¹. The analysis of the products showed that the degradation of anthocyanins was affected mainly by the airflow rate and, thanks to the structure of the SBR, the powder content achieved high values and the moisture was kept low. The study conducted by Araújo and colleagues [19] used a conical SBR for drying a probiotic juice made of acerola juice and sugars while keeping the properties of the probiotic. The powder was dried at 60 °C and the moisture level was reduced to 1.91%. *Syzygium cumini* residue [20] presents a high antioxidant, anthocyanins and mineral content. For this reason, the effect of temperature and residence time during a drying process in a cone–cylindrical SBR was analysed. A 0.630 kg amount of biomass was fed continuously and dried at 105 °C to obtain a decrement of moisture content from 59 to 72 g 100 g⁻¹ to 4–9 g 100 g⁻¹. The results confirmed the efficiency of this technology, with a low loss of antioxidants

(3–7%) and a good degradation of anthocyanins (60–70%). Another study [21] compared the quality of the product obtained after a drying process in a spray dryer and in an SBR for the production of bio-oil. Papaya seeds were used for this analysis and the best results in terms of oil extraction ($26.5 \text{ g } 100 \text{ g}^{-1}$) were obtained at $70 \text{ }^\circ\text{C}$ for 4 h. The moisture content decreased from $40 \text{ g } 100 \text{ g}^{-1}$ to $11\text{--}13 \text{ g } 100 \text{ g}^{-1}$. A probiotic fruit juice [22] was used as feedstock for a drying process conducted in a spray drier at $140 \text{ }^\circ\text{C}$ and in an SBR at $60 \text{ }^\circ\text{C}$. The results demonstrated the advantage of using an SBR for maintaining the characteristics of the probiotic product and reaching low moisture content (under 3%) by working at lower temperatures.

The advantages provided by SBR have been studied for increasing the quality of roasted coffee beans [23]. An SBR equipped with a draft tube was used. The roasting process was conducted at $210 \text{ }^\circ\text{C}$ for 22 min and the obtained dried product was treated with a cryogenic cooling. The process yielded a higher retention of volatile compounds and less burning of the surface compared to a conventional process. A conical SBR was studied by Chielle and colleagues [21] using papaya seeds as feedstock. They concluded that the most adequate drying conditions to obtain high oil extraction yields were air temperature at $70 \text{ }^\circ\text{C}$, air velocity at 10.5 m/s and drying time of 4 h. Another study [24] investigated how much the temperature influenced the characteristics of semi-refined carrageenan dried in an SBR at 60, 100 and $150 \text{ }^\circ\text{C}$. An increase in temperature resulted in a decrease in the moisture content and in the drying time but provided a lighter colour. The best temperature in terms of process time and characteristic of the product was $100 \text{ }^\circ\text{C}$. Huang and collaborators [25] reviewed the application of SBR for the drying of solid and liquid food products such as seeds, grain, rice, anchovy, coffee beans, soybeans, wheat, peas, milk, orange juice and fruit pulp. The obtained results demonstrated that the use of auxiliary devices such as draft tubes, fountain confiners or the use of specific reactor shapes (such as rectangular SBR) considerably increased drying yields. Butzge and collaborators [26] investigated the efficiency of a conical SBR for drying bovine hydrolysed collagen (BHC). Thanks to several tests at different working conditions, they discovered that the maximum powder production could be obtained by working with polypropylene as inert material and atomisation as feed mode. A mechanical modified spouted bed reactor (MMSB) fitted with a helical screw was analysed for the drying of alumina and skimmed milk [26]. The tests showed that the helical screw decreased the air velocities needed for the running of the reactor, decreasing the total energy consumption [27]. Another study conducted by Sousa and colleagues [28] investigated the advantages of introducing an open helicoidal conveyor screw above the air inlet orifice for improving the flow. The tests demonstrated that the flow needed to achieve the same yields as conventional SBR was 50% lower, providing a higher energy efficiency.

The effect of solar-assisted spouted bed and open sun drying on the drying rate and quality of the products was studied using peas as feedstock and a cylindrical spouted bed coupled with a solar collector to get hot air [29]. The process was carried out with 250 g of samples that were monitored every 30 min calculating the drying efficiency. The results showed that the solar-assisted SBR had a higher drying rate and lower drying time compared to open sun drying, even if the quality of the products was similar for both designs.

Reyes et al. [30] analysed the yield of the drying of sawdust in a rectangular SBR by using solar energy to heat the drying air. The study demonstrated that working with a solid flow inlet of 550 g/min and a T_{air} around $50 \text{ }^\circ\text{C}$, the moisture content was reduced by 20.5 wt%. The effect of increasing the number of units of the spouted bed system was also evaluated, which resulted in a greater influence on the decrease in the moisture content of the sawdust with respect to increasing the drying temperature by $10 \text{ }^\circ\text{C}$.

An interesting study analysed the efficiency of superheated steam to dry sawdust using two different conical SBRs [30]. Both reactors showed good results, even if the heat flux was not enough for obtaining a complete drying of products, due to the small volume of the chamber [31].

In another study, a rectangular SBR was used for drying millet particles [32]. The reactor was equipped with a pressure and an acoustic transmitter and an electrical capacitance tomography system (ECT). The batch process was conducted with 1.8 and 2.5 kg of materials. Thanks to these sensors, it was possible to study the fluid dynamic behaviour of the reactor more precisely.

Runha and colleagues [33] studied the development of a spouted bed to produce dry extracts of medicinal Brazilian plants. The plants used for the experiment were *Passiflora edulis* and *Passiflora alata*, and, in particular, the leaves from which the desired compounds were extracted. Afterwards, the extracted solution was weighed and concentrated. A cylindrical spouted bed was used for drying the solution. The study confirmed that the high heat transfer rate and the good mixing of particles that a spouted bed achieves increased the quality of the product with drying yields obtained at lower temperatures compared to traditional processes.

The performance of a conical SBR for the drying of *Lippia sidoides* was studied by Benelli and colleagues [34]. Several tests were conducted at different working conditions and the results were compared with those using a spray dryer. The moisture and the water activity in the product obtained with the SBR were very low, showing the good performance of the reactor.

Beigi and colleagues [35] investigated the drying of thorium oxalate slurry in a conical SBR filled with inert glass spheres. Three different temperatures (90, 100 and 110 °C) and three air inlet velocities (1, 1.2 and 1.5 times the minimum spouting velocities) were tested during this study. A temperature of 110 °C and the highest flows gave the optimised drying results.

To enhance the quality of SBR, novel intensification structures have been studied [36]. Wu and colleagues compared the drying rate, the unit energy consumption and the bed pressure drop between a conventional SBR and the ones equipped with an intensification structure: one reactor presented an integral swirling blade nozzle (ISBN), another one a spherical longitudinal vortex generator (LVGs) and the last one an integral multi-jet spout-fluidised bed (IMJSFB). To fit the data, the Weibull distribution function was introduced. In the tests, activated alumina (Al_2O_3) was completely immersed in water until the particles reached a moisture content of $0.50 \pm 0.01 \text{ kg}_{\text{water}}/\text{kg}_{\text{dry material}}$. The air-drying process of these particles on different reactors showed the strong and weak points of these technologies. For example, compared with the conical SBR, the LVGs and the IMJSFB reduced the activation energy of the drying process, while the ISBN increased this value. Also, ISBN caused a larger bed pressure drop, while LVGs showed only a slight increment. Only the IMJSFB showed a reduction in this value. A critical point was the decrease in the drying rate in the bed of the reactor equipped with LVG, due to the liquid bridge force between wet particles that makes the particles in the LVGs easier to bond. The novel technology that reached the best results was the IMJSFB. In fact, compared with the conical SBR, the average drying rate was increased by about 8.6%, while the unit energy consumption and the average pressure drop were decreased, respectively, by 8.2% and 9.5%. The best results were obtained by working with a particle diameter of 2 mm. This technology seemed also the most suitable for a possible scale-up of the plant.

3.1.2. Coating

The coating is applied in several fields such as food, detergents, fertiliser and mostly for pharmaceutical applications. The purpose of the coating is to create a homogeneous film around particles without the presence of cracks and to protect the core material from the environment or the release of material. The coating is applied to active substances that need to be released under defined conditions, for example in a certain pH (like in the gastrointestinal apparatus or in the agriculture fields) or in a certain time frame. The development of SBR has given excellent results in this field thanks to the high mixing degree achieved and turbulence inside the reactor which helps in the fluidisation of coarse and cohesive particles preventing problems of segregation that might occur in FBR [37].

Coating has found an important application in the nuclear fuel field. In fact, coating on fuel kernel particles helps the containment of radioactive products and the sustainment of the internal gas pressure, which represents the first barrier to the safe operation of the reactor. Guo and collaborators [38] demonstrated that the use of SBR for chemical vapour deposition provided good results, producing coated particles with a uniform, highly dense and pure phase coating layer.

A conical SBR equipped with different draft tubes (different diameters and positions) was used for the coating of group B iron powders (44–88 μm) with an aqueous solution of polyethylene [39]. The results showed that by increasing the entrainment length, the amount of coating increased, while the diameter of the draft tube was not found to affect the process. The maximum coating mass fraction achieved was 0.78 wt%.

A ProCell type SBR was used for the mixing of sub-micron homo-aggregates of dried Al_2O_3 and dried TiO_2 to produce hetero-aggregates [39]. The high mixing degree achieved by spouted beds resulted in good results, with high values of HoM_m (modified homogeneity of mixing) inside single agglomerates [40].

3.1.3. Desulphurisation

Desulphurisation has an important impact on the environment and human life since the production of large quantities of SO_x and CO_2 is a critical issue for environmental safety. Wu and colleagues [41] studied the possibility of using SBR for removing SO_x with the addition of limestone inside the reactor. The desulphurisation efficiency of the spouted bed increased in the first instance and then decreased with the increase in the water content of the desulphurisation slurry. The optimum slurry water content for the desulphurisation process in powder–particle SBR was $40 \text{ kg}_{\text{H}_2\text{O}}/\text{kg}_{\text{dry_sorber}}$, obtained by numerical simulation. The removal of SO_2 at the end of the process with this slurry water content was 75.75%. It was also noticed that the desulphurisation of the gas flow took place principally in the annulus zone thanks to the large particle's concentration. The same authors carried out a study on the semidry flue gas desulphurisation in a two-dimensional spouted bed reactor. The flue gas, which contains SO_2 , is treated with water and a slurry of $\text{Ca}(\text{OH})_2$. Different tests were conducted with different gas flow rates (4.5–6 m^3/h) and temperatures (maximum 520 K). The best results were obtained by working with an inlet temperature of 480 K, reaching a desulphurisation efficiency of 84% [42].

Che, Wu and Wang [43] conducted the same desulphurisation process in four different reactors: a conventional spouted bed (CSBR), a spouted bed with longitudinal vortex generator (SB with LVG), an integral multi-jet spouted fluidised bed (IMJSFB) and a spouted bed with swirl blade nozzle (SB with SBN). The purpose of the experimental study was to demonstrate that novel intensified SBR can achieve better results compared with conventional spouted beds. The results confirmed the hypothesis, with the desulphurisation efficiency of a CSB equal to 77.75%, and the desulphurisation efficiencies of the SB with LVG, IMJSFB, and SB with SBN equal to 80.85%, 87.97%, and 88.81%, respectively.

A spouted bed equipped with a swirling blade nozzle structure was used for the treatment of a sulphur-containing gas [44]. The gas entered from the bottom of the reactor while the desulphurisation slurry, composed of $\text{Ca}(\text{OH})_2$ entered from the top of the reactor. The use of a swirling blade nozzle increased the heat and mass transfer rates, with a consequent increment of the temperature inside the reactor (compared to the same process with a conventional spouted bed). The desulphurisation efficiency with this technology was increased from 76.14% to 85.42%, showing the potentiality of this novel structure.

3.1.4. Thermo-Chemical Processes

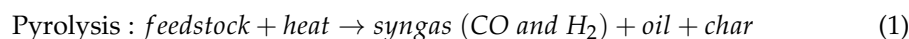
Renewable energy from thermo-chemical valorisation processes is playing a key role in today's energy outlook. The possibility of valorising waste to produce environmentally friendly energy and fuels is becoming a reality. SBRs stand out as a promising player thanks to their ability to handle residues of different densities and sizes without significant

segregation phenomena and with vigorous solid movements resulting in high heat and mass transfer rates between phases (as described in Section 2).

Thermo-chemical reactions include pyrolysis, combustion or incineration and gasification reactions, which may generate intermediate valuable products (mostly hydrocarbons and syngas which can be further converted into added-value fuels, electricity, or heat) or CO₂ and water as final products (maximum generation of heat). Biomass and agricultural residues are good candidates to be used as feedstock, due to their wide availability and renewable nature and their chemical properties, such as their high carbon and oxygen content [45]. A review of the different thermo-chemical reactions (i.e., pyrolysis, combustion and gasification) is discussed in the following paragraphs.

➤ Pyrolysis

Pyrolysis is an endothermic thermal decomposition of the solid feedstock in the absence of oxidant agents occurring at low–medium temperatures, in the range of 300–600 °C (Equation (1)). The products are gaseous substances, oils and the carbonaceous residue, char. The presence of vapour inside the reactor can favour the water gas shift reaction (Equation (2)), increasing the production of hydrogen [46]. A review of the different feedstocks used for pyrolysis reactions is discussed in the following paragraphs, with a summary of some applications gathered in Table 2.



• Biomass

A conical SBR equipped with a non-porous draft tube reactor was used for a fast pyrolysis reaction of two different types of pinecones, focusing mainly on biochar production. The tests conducted showed that the highest quantity of biochar (32.36 wt% for one of them and 31.52 wt% for the other) was obtained at 500 °C while increasing the temperature decreased the production of biochar in favour of lighter compounds [47]. The fast pyrolysis of rice husk, where the feedstock is rapidly heated to high temperatures to maximise the production of the liquid product fraction [48] was conducted in a conical SBR to produce bio-oil [49]. The process was carried out in the range of 400–600 °C and the optimised condition was found at 450 °C, where the bio-oil yield reached 70 wt%. The increase in the process temperature resulted in an increase in the production of light molecules and a decrease in bio-oil and char. The same reactor was used for the valorisation of citrus wastes [50]. The bio-oil yield was high (around 55 wt%) in a temperature range of 425–500 °C and with a continuous feeding of 200 g/h. The content of methanol and furfural was higher compared to the bio-oil produced with lignocellulosic biomass, but the high production of char and the high concentration of CO₂ in the gas could be important drawbacks.

A micro SBR was used by Xu and colleagues for studying the kinetics of a fast pyrolysis reaction, in particular the pyrolysis of rice husk [51]. The tests demonstrated that by raising the temperature from 773 K to 1173 K the reaction time decreased to 3.5 s. CO was the first product obtained, while CO₂ and CH₄ presented the slowest reaction rate curves.

The efficiency of the fast pyrolysis of eucalyptus wastes in a conical SBR was studied [52]. The process, carried out at 500 °C, produced 75.4 wt% of bio-oil with low concentrations of N and S compounds. Du and colleagues [53] analysed the composition of the product obtained from the fast pyrolysis of miscanthus x giganteus in a conical SBR with a ZSM-5 catalyst, in a range of 400–600 °C. Increasing the temperature of the process, the quantity of gas produced with the fast pyrolysis increased and the production of bio-oil decreased. Three different microalgae species were studied to produce biofuel through pyrolysis in a continuous bench-scale conical SBR [54]. The inlet was composed of freeze-dried microalgae (*Nannochloropsis* (NC), *Tetraselmis* (TS) and *Isochrysis galbana* (IG)) and nitrogen. The reaction was carried out in continuous mode by feeding 1 g/min

of microalgae at 500 °C. To increase the heat transfer, a bed of sand was placed inside the reactor. The main product of the reaction was bio-oil, and its yield was affected by the species of microalgae used. *IG* presented the higher production of bio-oil thanks to the higher presence of volatile compounds compared to the other two species. Bio-oil was mainly composed of hydrocarbons, nitrogen-carbonated compounds (NCC) and oxygenated compounds. Barcelos and colleagues [55] studied the segregation of particles during a pyrolysis process in an SBR. The biomass used for the experiment was a mixture of sand–coconut shells and sand–cocoa shells and the results showed that cocoa shells were the most suitable for the process thanks to their flowability and the best results were obtained with a mixture of 75 wt% of cocoa shells and 40 wt% of coconut shells, with a good mixing and flowability.

A torrefaction process at a maximum of 300 °C was carried out in a dual-compartment slot rectangular spouted bed reactor with pinewood sawdust as feedstock [56]. The mass loss achieved was 9.3–38.2 wt% and valuable liquid and gas products were produced, such as aromatics and traces of H₂ and CH₄ (even if the gas is composed mainly of CO and CO₂). This reactor could be simply scaled up and used for treatment at the industrial level.

- Sludge

A conical SBR was used for studying the stability and the efficiency of a fast pyrolysis reaction, using a co-feeding of sewage sludge and pinewood sawdust [57]. The results were compared with fast pyrolysis reactions of the single materials. The reaction was carried out at 500 °C, with pure pinewood sawdust, pure sewage sludge and a 50% mixture of them. It was noticed that the ash produced from the pyrolysis of pinewood sawdust decreased the temperature needed for the degradation of the sludge. The low residence time and the high heat transfer rates resulted in a high production of bio-oil in all three cases. The pyrolysis of pure sewage sludge was analysed in a temperature range of 450–600 °C and the maximum liquid yield obtained at 500 °C was 77 wt%. The liquid was mainly composed of water, and oxygen-containing and nitrogen-containing compounds. Char removal significantly increased the efficiency of the process, avoiding its accumulation in the bed [58–60].

- Plastics

The valorisation of plastic waste to produce added value molecules represents an interesting perspective for the future. Different research teams have studied the performance of SBR for the pyrolysis of plastic materials, for example, Ibáñez and colleagues [61] conducted experiments on a system composed of a conical SBR and a fixed bed reactor for the pyrolysis cracking of HDPE, using HZSM-5 zeolite as catalyst. The purpose was to study the coke deposition on the catalyst and, consequently, the reduction in the efficiency of the process. The tests, at 500 °C, showed that the pathway for coke formation was in two steps: initiation (production of coke during the first hour) and steady coke formation, which was more severe and caused the degradation of the micropore area and the Brønsted acidity of the catalyst. Borsella and collaborators [62] compared the use of HZSM-5 zeolite and an iron-alumina pillared montmorillonite for the pyrolysis cracking of HDPE in a conical SBR. The zeolite gave significant yields of gaseous products (over 74 wt%), while the latter provided high yields of waxes, mainly C11–C21.

The recovery of styrene from polystyrene by flash pyrolysis was studied in a conical SBR in the temperature range of 450–600 °C and a variable spouting velocity from 1.25 to 3.5 times the minimum one. The results showed a maximum yield, 70.6 wt%, obtained at 500 °C and a gas velocity twice the minimum one [63].

A conical SBR equipped with a non-porous draft tube and a fountain confiner was used for the pyrolysis of LDPE, HDPE, PP, PS, PET and poly(methyl methacrylate) (PMMA) [64]. A spent fluid catalytic cracking (FCC) catalyst was based on a zeolite active phase. PS and PMMA were the polymers that required a lower temperature (420 and 470 °C) for their degradation under stable operating conditions, while a higher temperature (710 °C) was needed for PET. The temperature of the process is a critical parameter since a major risk in spouting regimes is bed defluidisation. The tests showed that the presence of a draft

tube and a fountain confiner improved the stability of the process, the turbulence, and the heat transfer rate. Increasing the ratio between the mass of the bed and the plastic flow resulted in a decrease in the temperature needed for the reaction, reducing the energy needed. Also, the use of a spent FCC catalyst decreased the process temperature since it promoted cracking reactions. A higher spouting velocity increased the turbulence inside the reactor and, consequently, the gas–solid contact. Artexte and collaborators [65] studied the efficiency of a system composed of a conical SBR and a fixed bed catalytic reactor for the cracking of HDPE. The catalyst used was a HZSM-5 zeolite at different SiO₂/Al₂O₃ ratios (30,80 and 120). Both reactors worked at 500 °C and the maximum light olefin yield (58 wt%) was obtained with the lowest tested ratio. This study demonstrated the higher efficiency of SBR when compared with conventional reactors. A similar work [66] studied the catalytic cracking of HDPE and the use of the produced volatiles (mainly waxes) as feedstock in a catalytic fixed bed reactor. The cracking reaction of volatiles was enhanced by the increment of temperature inside the reactor. In fact, full conversion was obtained at 550 °C, with a yield of 52% of gasoline and 28% of light olefins.

- Other feedstocks

Hwang and collaborators used a conical SBR for the pyrolysis of waste tyres. The scrap of tyres had a carbon content of 82.85% and an HHV of 35.69 MJ/kg [64]. The purpose of the study was to find the best working conditions to produce oil and the recovery of D-limonene. Several tests were carried out in a range of temperature of 400–550 °C and three different feeding rates: 0.5–1–1.5 kg/h. The highest yield of waste tire pyrolysis oil (WTPO) was 67 wt% at 450 °C. An optimised product in terms of energy content was obtained at 500 °C (44.7 MJ/kg and 1.2 wt% of water content). Also considering the recovery of D-limonene, the best-applied conditions were 450 °C, 1 kg/h of feed and 4 h of distillation. From 1 kg of scrap, 5.65 g of D-limonene could be produced [67].

Table 2. SBRs used for pyrolysis reactions.

Feedstock	Type of Reactor	Temperature	Yield of Main Target Products	Reference
Pinecones	Conical	500 °C	32 wt% biochar	[47]
Rice husk	Conical	450 °C	70 wt% bio-oil	[50]
Eucalyptus waste	Conical	500 °C	75 wt% bio-oil	[52]
Sludge	Conical	500 °C	77 wt% bio-oil	[58]
Polystyrene	Conical	500 °C	71 wt% styrene	[63]
Waste tyres	Conical	450 °C	67 wt% bio-oil	[67]

➤ Combustion

Combustion is the complete oxidation of the feedstock, a strongly exothermic reaction, mainly used to produce heat and to reduce the volume of waste. This reaction occurs in excess of oxygen, to produce CO₂ and H₂O. The heat released can be used to produce high-pressure steam addressed to turbines to produce electricity. Attention must be paid to the quality and quantity of produced ashes, as they can lead to corrosion and slagging phenomena, affecting the physical structure of the reactor [68]. Table 3 gathers some applications of SBR used to carry out combustion reactions.

- Biomass

San Josè and colleagues [69] studied the possibility of using a conical SBR for the combustion of avocado seeds and skins. Avocado is a fruit with a medium/high concentration of C, making it suitable for a combustion/gasification process. The study focuses on the combustion efficiency of seeds, skins and a mixture of them at different temperatures, in order to identify the best working conditions. The experiments demonstrated that the higher combustion efficiency was reached by working with only avocado skins, and this value decreased with the increase in the concentration of avocado seeds. At 475 °C, the combustion efficiency was already at 95%, while the best results were obtained at 600 °C.

A conical SBR was used by San José and colleagues for the thermal exploitation of wastes from pruning vineyards obtaining satisfactory results [70]. A similar study was conducted using fruit tree pruning wastes, where high combustion efficiencies were also obtained, working with different gas inlet temperatures (25, 50, 75 and 100 °C). By keeping the temperature for the combustion reaction around 425–550 °C, a combustion efficiency of 85–92 wt% was obtained [71]. The Pd/Al₂O₃ catalyst was used to increase the efficiency of the combustion process. Thanks to this catalyst, the temperature needed for the complete combustion of waste was reduced to 320 °C, much lower than the 450 °C needed when working without a catalyst [72].

Table 3. SBRs used for combustion reactions.

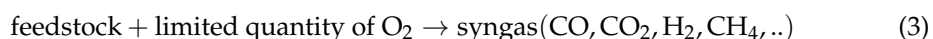
Feedstock	Type of Reactor	Temperature	Yield of Reaction	Reference
Avocado seeds and skins	Conical	475 °C	95 wt%	[68]
Pruning vineyards	Conical	425–550 °C	85–92 wt%	[71]
Sludge	Conical	600 °C	84 wt%	[72]

- Sludge

Energy valorisation from the combustion of sludge wastes from a paper industry was studied in a conical SBR. The process was carried out at 500–700 °C with sand beds for improving the combustion efficiency. At 600 °C, with the sludge waste dried for 10 min at 105 °C, the combustion efficiency was 84 wt% [60].

- Gasification

Gasification is an intermediate endothermic reaction, between combustion and pyrolysis, involving partial oxidation of the fuel. The oxidant agent, normally air or pure O₂, is supplied in a restricted quantity, so the feedstock is not completely oxidised (i.e., sub-stoichiometric), at temperatures typically above 800 °C [5]. The main products are H₂, CO and CO₂ (Equation (3)) and the partial combustion (or an external heat supply) energetically sustains the process. As an example, Table 4 gathers the H₂ production yields of gasification reactions using SBR.



- Biomass

Remón and colleagues [73] studied the production of hydrogen starting from bio-oil. For their experiments, they used two different reactors, a conical SBR and a FBR with the same feedstock (pine sawdust). Successively, they studied the hydrogen yield of a catalytic and non-catalytic steam reforming step. The catalytic process was carried out in two different reactors, a fixed bed and a fluidised bed. The catalyst used was made of Ni-CO/Al-Mg and two different feedstocks were used in both cases, the bio-oil and the aqueous fraction of bio-oil. The highest yield was obtained from the catalytic steam reforming in the fixed bed reactor with the aqueous solution was 0.17 g H₂/ g organics, while the lowest result was obtained from the catalytic steam reforming of the aqueous solution in the fluidised bed (0.07 g H₂/ g organics). A conical SBR was used to evaluate the evolution of the yield of hydrogen in the reforming step of bio-oil, in particular ethylene glycol and acetic acid [74]. An Ni/olivine catalyst was added inside the reactor to increase the conversion and selectivity to hydrogen. The conversion of ethylene glycol at 750 °C was complete (mainly in H₂ and CO_x) while the conversion of acetic acid, conducted always at 750 °C, proceeded more smoothly. The H₂O/C ratio increment increased also the hydrogen selectivity, with a value over 90% when the ratio is 4.6.

A fountain-confined conical SBR was used to produce syngas from bio-oil [45]. The biomass used to produce the bio-oil was forest pinewood waste, previously crushed and grounded to a particle size of 1–2 mm and dried to a moisture content below 10 wt%. The higher heating value (HHV) was 19.8 MJ/kg. Pyrolysis and steam gasification reactions

were performed in the same reactor, placed inside a radiant oven, which provided the required heat for operating up to 900 °C. For maximising the production of bio-oil the inlet (0.75 g/min of biomass) was fed at 500 °C. The gas phase was composed of nitrogen and vapour since the pyrolysis reaction worked in the absence of oxygen and vapour was needed for the gasification reaction. By working with a steam/biomass ratio of 2, the tests demonstrated that carbon conversion, and consequently syngas production and tar reduction, increased with the temperature, reaching a value of 96.3% at 900 °C. Also, the hydrogen content increased with temperature, with a value of 7.96% at 900 °C and an H₂/CO ratio of 2. Tar was mainly composed of light PAHs in a more significant concentration at high temperatures compared to heavy PAHs.

The efficiency of a conical continuous SBR was studied for the pyro-gasification (combination of pyrolysis and gasification to increase the yield of hydrogen principally [75]) of pinewood sawdust [76]. The study analysed the influence of different variables on the yield, such as temperature, steam/biomass ratio and diameter of particles. The bed was filled with silica to enhance the solid circulation and heat transfer. Tests demonstrated that an increment of the temperature and the biomass/steam ratio had a positive effect on the production of H₂ while decreasing char and tar contents. The particle size did not seem to influence the process.

Olivine and γ -alumina were used as catalysts for the steam reforming of pinewood sawdust [77]. The purpose was to analyse how much these two catalysts could decrease the production of tar and increase, consequently, the percentage of light products. Olivine and γ -alumina reduced the production of tar by 79% and 84%.

Lopez and colleagues analysed the influence of HDPE co-feeding on the yield of a pyro-gasification process of pinewood sawdust in a conical SBR [78]. Tests were conducted at 900 °C, with a steam/biomass + plastic ratio of 1 and olivine as the primary catalyst. The co-feeding of HDPE decreased sharply the production of tar and char, with the tar going from 58.23 g Nm⁻³ for pure biomass to 9.74 g Nm⁻³ for the 50% mixture with HDPE.

Another study by Fernandez et al. [79] analysed the role of temperature in biomass steam pyrolysis in a conical spouted bed by using sawdust pinewood (1–2 mm) as a solid inlet. The analysis focused on the hydrogen production. The range of temperature used for the runs was 500–800 °C. At 500–600 °C, the main reaction was pyrolysis, and the steam had a strong influence on the composition of the product and the percentage of volatiles. The increment of the temperature to 700 °C showed a lower influence of the steam on the process and a higher percentage of the bio-oil product. At 800 °C, the reaction pathway was controlled by gasification. In fact, the results showed that a higher yield of volatiles was obtained with higher temperatures (from 7.3 wt% at 500 °C to 63.9 wt% at 800 °C). At the same time, the yield of liquid compounds harshly fell (from 75.4 wt% at 500 °C to 27.2 wt% at 800 °C) while the solid fraction was less affected by temperature (from 17.3 wt% at 500 °C to 8.9 wt% at 800 °C). The concentration of CO and CO₂ decreased at higher values of temperature while the concentration of H₂ increased. The bio-oil at 500–700 °C was mainly composed of phenols, while at 800 °C the main fraction was composed of PAHs.

A conical SBR equipped with a non-porous draft tube and a fountain confiner was used for the pyro-gasification of pinewood sawdust [80]. An olivine catalyst was used to enhance the production of hydrogen. The aim of the study was to investigate the effect of temperature on the process. An increment of the temperature, coupled with the catalyst, considerably reduced the production of tar and char, increasing consequently the production of syngas and H₂. At 900 °C, in fact, the hydrogen yield reached a value of 7.28 wt%. In a second study [81], a Fe/olivine catalyst was used for the biomass steam gasification process. The catalyst was prepared by wet impregnation of the olivine support with an aqueous solution of Fe(NO₃)₃·9H₂O, with a final product composed of olivine and 5 wt% of Fe. Tests were conducted at 850 °C using steam as a fluidising gas. Prior to the reactions, the iron catalyst was subjected to an in situ reduction process at 850 °C for 4 h with a stream containing 10 vol% of H₂ to ensure complete reduction to the Fe⁰ phase. The tests conducted proved that the iron incorporation had improved the syngas production

and composition and had reduced the tar production, in fact, gas production was increased from 1.30 Nm³/kg with calcined olivine to 1.46 Nm³/kg with Fe/olivine catalyst, and similarly did the hydrogen production, with the value being 6.25 wt%. Likewise, tar concentration was reduced approximately to half, from 20.6 to 11.4 g × Nm³. The catalyst deactivation was due to the oxidation of the metallic iron into Fe₃O₄.

A conical SBR and an FBR were used for the pyrolysis and steam reforming of pinewood sawdust, with the aim of analysing the product obtained from the reactions and the evolution of the process in the time [82]. A calcium-promoted nickel-based catalyst was used in the steam reforming process to increase the quality of the process. The pyrolysis was carried out at 500 °C, while the steam gasification temperature was 600 °C, obtaining a conversion of 99.7 wt% and a hydrogen yield of 93.45 wt% (11.2 g of hydrogen for 100 g of biomass). Increasing the reaction time, the deposition of coke on the catalyst increased, reducing the activity and the efficiency of the process. The co-feeding of HDPE was investigated to optimise the hydrogen production [83]. The results showed that thanks to HDPE, the production of H₂ increased from 10.9 g for 100 g of feed (no HDPE) to 37.3 g for 100 g of feed (only HDPE). The pyrolysis and steam reforming of pinewood, citrus wastes and rice husk were carried out in a similar system [84], with a calcium-promoted nickel-based catalyst used in the steam reforming process. The purpose of the study was to compare the product obtained from the pyrolysis, the reforming of the different materials and the evolution of the process inside the reactor. The pyrolysis reaction occurred at 500 °C while the steam reforming at 600 °C with a S/B ratio of 4. The conversion in all three cases was around 99% but the composition of the products changed significantly. In fact, the production of H₂ decreased as follows: pinewood (11.2 wt%), rice husk (10 wt%) and citrus wastes (6.7 wt%). The catalyst deactivation occurred due to the presence of coke and oil, mainly with citrus wastes and rice husk due to the formation of encapsulating coke.

Another process [85] was carried out in a two-reactor system composed of a CSBR and an FBR, with Ni/Al₂O₃ used in the FBR as a catalyst to improve the steam-reforming reaction of pine sawdust. The process allowed the production of 10.5 wt% of H₂ (steam reforming at 600 °C, S/B ratio 4 and space time of 20g_{cat} min gvolatiles⁻¹) but the deactivation of the catalyst was significant, remaining still an open question that needs to be solved. A two-reactor system, composed of a conical SBR and an FBR, was used for the gasification of pinewood sawdust, using an Ni-based catalyst supported on Al₂O₃ and doped with Ca [86]. Different tests demonstrated that the highest concentration of H₂ (8.30 wt%) was obtained at 600 °C for the steam reforming process with an S/B ratio of 3 and an ER of 0.12. Feeding pure O₂ improved the quality of the process, and it was found that the design of a multi-point injection helped in avoiding the creation of dangerous hot spots.

An interesting study was conducted on the gasification of wood by a direct irradiated hybrid solar/combustion SBR [87]. In an autothermal gasifier, the required process heat is supplied by burning 30% of the feedstock, with a considerable loss of the yield of the process. The use of concentrated solar energy to reach the high temperature needed for the endothermic reaction was studied. In this way, the yield and the quality were increased, since there was a higher concentration of carbon, and it was possible to maintain the right ratio between C and H₂. However, solar energy is variable during the day and during the seasons. For this reason, a hybrid process that supplies energy from the sun and from the combustion of biomass was found to be the best solution. The study concluded that the use of a hybrid system increased the yield of the reaction and the stability of the syngas produced, reducing the concentration of CO₂ produced during the combustion reaction.

There are different studies on solar spouted beds since they represent a clean, efficient and environmentally friendly technology. Li and colleagues [88] analysed the gasification of pinewood in a solar-spouted bed. The process was carried out with solar energy as the only heat supply. The results confirmed the obtainment of high yields with a maximum carbon conversion of 86.69% and a gasification efficiency of 92.29%.

Different tests were carried out using a fluidised SBR with three different feedstocks: coal, marine microalgae and a blend of leached microalgal biomass and coal [89]. The

purpose of these experiments was to find the best conditions for obtaining the highest hydrogen yield, with the variation of three conditions: air-to-fuel ratio (A/F), steam-to-fuel ratio (S/F) and bed temperature (T_b). The results showed that the optimum operating conditions using coal were $A/F = 1.82$, $S/F = 0.75$ and $T_b = 850$ °C, with an H_2/CO ratio = 2. In the other two different cases, the results were unsuccessful.

- Plastic

Plastic consumption has increased in the last decades, and its short lifetime is creating a large quantity of waste. The necessity of a better recycling strategy in a circular economy view has been a core issue in the last few years. Landfilling and incineration do not represent a valuable solution for this problem, and alternatives such as thermochemical reactions can represent a promising solution. The coupling of pyrolysis and gasification can produce added-value products such as syngas and hydrogen and valuable chemicals such as light olefins or aromatics. Since this reaction can produce a wide number of products, the use of a catalyst to increase the selectivity of a target product is crucial. Orozco et al. [90] carried out a study using HDPE as feedstock in a conical spouted bed, to evaluate the influence of oxidative conditions on the deactivation of an equilibrium FCC catalyst. The reactor was equipped with a draft tube and fountain confiner for improving the mixing of solids and gas and to decrease the pressure drop. A space time of $15 \text{ g}_{\text{cat}}\text{min}/\text{g}_{\text{HDPE}}$ was selected for the runs, with a bed composed of a mixture of 135 g of sand and 15 g of equilibrium FCC catalyst. The process occurred at a temperature of 550 °C. In the conventional process, the gas flow was constituted only by nitrogen while in the oxidative pyrolysis runs a mixture of nitrogen/oxygen was used, with 7.4% vol of O_2 . The use of oxygen in the fast pyrolysis of HDPE increased the yield of valuable chemicals, to 29 wt% of light olefins. The efficiency of the process was also improved. In fact, after 90 min, waxes were fully converted, in contrast with the conventional reactor runs where, after 60 min, waxes were still unconverted. A concentration of coke three times higher than that in the conventional reactor was found, since light olefins are the main coke precursors in the cracking of plastics on the FCC catalyst.

The steam gasification of HDPE in a conical spouted bed was studied at different working conditions to determine its optimal conditions [91]. Olivine and γ -alumina were used to minimise the formation of tar. At 900 °C and a steam/plastic ratio of 2, a carbon conversion of 93.6%, with 61.6% vol of hydrogen and 4.8% vol of tar with olivine as catalyst was obtained [92]. Another experiment evaluated the steam reforming of HDPE in a system composed of a conical SBR and an FBR. The steam reforming reaction was carried out with an Ni-based catalyst. Different temperatures and steam/plastic ratios were tested, and the maximum yield of hydrogen (92.5%) was obtained at 700 °C and an S/P ratio of 5, with a production of 38.1 g of H_2 per 100 g of HDPE in the feed. A different study [93] analysed the hydrogen production from HDPE via steam reforming. The system was composed of a conical SBR and a fixed bed reactor with an Ni-based catalyst. The maximum H_2 yield obtained at 700 °C was 36 wt% with 94% conversion of CH_4 .

The hydrogen production was investigated using polystyrene as a feedstock in a system composed of a conical SBR and an FBR [94]. An Ni-based catalyst was used in the steam reforming process, carried out at 700 °C, while the pyrolysis was carried out at 500 °C. The production of hydrogen was equal to 29.1 wt% and the catalyst was found to be affected by the aromatic nature of the PS thermal degradation products.

Table 4. H_2 production using SBR through gasification.

Feedstock	Type of Reactor	Temperature	Yield of H_2	Reference
Pinewood sawdust	Conical	600 °C	11.2 wt%	[84]
Pine sawdust	Conical	600 °C	10.5 wt%	[85]
Pinewood sawdust	Conical	600 °C	8.3 wt%	[86]
HDPE	Conical	900 °C	61.6% vol	[91]
HDPE	Conical	700 °C	36 wt%	[93]
HDPE	Conical	700 °C	29.1 wt%	[94]

- Other feedstocks

Flame retardant products at disposal generate various ecological hazards and, for this reason, a gasification process can be an interesting valorisation of this waste. The reactions were carried out in a square-based SBR [95] and the results showed that the temperature had a strong effect on the conversion and characteristics of the product. In fact, an increment in the production of gas and, in particular, of H₂ was observed from 800 to 900 °C, together with a decrease in tar.

3.1.5. Other Processes

SBRs have been studied for different types of processes such as reduction reactions, extraction processes or water treatment.

Catalytic cracking [96] is used for obtaining products of commercial interest from lower aggregate value oils. Light gas oil (LGO) was used for a catalytic cracking reaction in an SBR using an FCC catalyst (synthetic faujasite type Y). The energy source was microwaved at 1500 W. The test showed that satisfactory results could be obtained at lower temperatures compared to conventional processes, with a reduction in energy costs.

Barrozo and collaborators [97] studied the possibility of using SBR for the extraction of natural dye from annatto (*Bixa orellana*). The conical–cylindrical spouted bed was equipped with a draft tube to increase the process efficiency. Two tests were conducted with 2 kg and 2.5 kg of inlet material, respectively. The Bixin content at the end of the experiment reached 48 wt% when the draft tube was used. A conical–cylindrical SBR equipped with a draft tube was used for the extraction of Bixin, a carotenoid, from annatto seeds [97]. The highest quantity of powder was extracted when the concentration of bixin at 30%. The maximum purity achieved was above 65%.

The possibility of using a novel SBR for the adsorption and electrochemical regeneration for water treatment was studied using bisulphate graphite as an adsorbent [98]. The removal of Acid Violet 17 was investigated, and the results showed that 98% of it could be removed at optimal conditions.

3.2. Demonstration/Industrial Scale Development

The scale-up of SBR from laboratory scale and their successful application to demonstration and industrial scales requires a deep knowledge of the reactor's fluid dynamic behaviour. The hydrodynamic stability must be conserved and that prevents the direct linear increase in geometric parameters (i.e., scale-up by increasing the dimensions of the reactor). Even though Epstein and Grace [1] proposed general criteria for their scale-up, the reality is that the question is still fully unsolved.

A possible alternative for an efficient scale-up is the design and construction of multiple interrelated units [2]. This strategy involves a careful optimisation of the geometry to minimise heat loss, investments, and operating costs. A simple start-up and process stability and performance should be ensured too. In this sense, square-based units could replace the traditionally applied round sections, which would create a more compact device.

Computational studies can help in this initial design phase. For example, Marchelli et al. [5] developed a fluid dynamic model to evaluate the solids residence time in a multiple unit spouted bed device. The tests proved the good mixing properties of the spouted beds, which create a stable fluidisation regime and do not feature dead zones.

Another computational study on a dual conical spouted bed system was carried out with the aim of developing a heat integration system based on continuous sand circulation from an exothermic to an endothermic reaction [99]. Different configurations were studied, depending on the feeding and discharge points of the interconnecting pipes: annulus–annulus, annulus–spout, fountain–spout and fountain–annulus. The SBR was equipped with a draft tube for improving the stability of the process and the material used for the tests was silica. The experiments showed that the fountain–annulus configuration was the most performant one, with a good solid circulation, a great stability even with small perturbations and low gas bypassing.

The simulation of coal-pressurised pyrolysis [100] was carried out by simulating an industrial-scale spout–fluid bed reactor ($H = 16.6$ m and $D = 3.1$ m) with a capacity of 500,000 tons/year. The flow pattern could be considered as a “jet in the fluidized bed with bubbling” and higher pressure improved the spouting and consequently the conversion. The reactor theoretically achieved the mass balance and the temperature of the outlet solid was stable around 600 °C. The increase in the semi-coke/coal ratio improved slightly the coal pyrolysis, but it also increased the number of particles inside the reactor, with a consequent increase in computational time. The particle size must be around 0–6 mm for keeping a good mixing of the solids.

Very few works can be found in the literature dealing with experimental studies on SBR. A conical spouted bed reactor SBR was designed and built for treating 25 kg/h of biomass [101]. The purpose is the production of bio-oil. The reactor was equipped with a draft tube in order to improve the mixing inside the reactor and the process efficiency. The best results were obtained by working at 480 °C, where the product was composed of 65.8 wt% of bio-oil, 18.8% of gas and 15.4% of char. The same reactor was used for the flash pyrolysis of poplar in a temperature range from 425 to 525 °C. The maximum yield of bio-oil (69%) was obtained at 455 °C [102].

Another important study has been conducted by Bove et al. [103] for the pyro-gasification of biomass in a pilot plant. The reactor is a square-based spouted bed that operates with 200 g/min of biomass (wood pellets and pruning wastes from apple trees) and can provide 20 KW_{th} . Two steps were followed for the start-up of the reactor: a pre-heating with a burner until 400 °C and a second heating through the combustion of wood pellets until 900–950 °C. The conversion achieved was high and a deep study was conducted on the char produced, by analysing the possibility of using it as a catalyst after as it is of after post-treatment.

Recently, a tentative successful scale-up of an SBR has been performed in the framework of the project Biochar [2]. The initial layout was designed to optimise the quantity and quality of char: the system is composed of 8 SB units (feed: 1 kg/min, potentiality: 750 kW_{th}) distributed in two differentiated stages: the combustion section in the lower part (four independent units) and the pyrolysis section (four interconnected units) in the upper part. Solids for combustion (wood pellet and pelletised textile waste) are fed continuously to the lower modules, which are independently controlled to achieve distributed optimal combustion rates. The reactors have a square base, which makes the device more compact, minimising heat losses, easing the scale-up process and decreasing investments. The produced heat is sent to the upper modules for pyrolysis to maximise the production of biochar. Here, solids are fed to the first unit and then progressively overflow to the downstream modules to become discharged from the fourth one as a pyrolysis product. In each module, the particulate solid is spouted by the gas formed in the corresponding lower stage, which is fed through an inlet located at the base of each unit. On the way out, the gas undergoes cyclone and scrubber cleaning.

4. Conclusions

Spouted bed reactors represent an interesting fluidisation technology for applications such as drying, coating or thermochemical processes, among others. Their characteristic fluid dynamic behaviour due to their geometric configuration leads to enhanced solid circulation rates and high mixing degrees, which also increases the mass and energy transfer rates. As a result of the review of works published in recent years, it can be stated that most of the reviewed experimental studies were carried out at a laboratory scale, with very few works dealing with larger scales. Despite the potential of this technology, achieving average efficiencies of 70 wt% of bio-oil or 90 wt% of syngas, its scale-up remains the most challenging issue for their successful industrial implementation. Advanced solutions such as multi-unit reactors or the use of rectangular geometries have arisen as potential scaled-up strategies that need further studies, while scientific questions are still open to discussion, for example, the design correlations at higher scales, which need full validation

or the need of models for the correct prediction of solid residence time distributions, which guarantee stability and optimal process performance.

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