Review Paper

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Fluidised Bed Reactors for the Thermochemical Conversion of Biomass and Waste†

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Abstract

The growing population and economic development globally has led to increasing resource consumption and waste generation. This has generated concern at local, national and international levels on environmental issues including air quality, resource scarcity, waste management (including plastics) and global warming. The resulting antipathy towards fossil fuels and waste landfilling has spurred the demand for alternative bioenergy and biofuels production methods, making use of abundant biomass and waste feedstock. Although not new concepts, there has been renewed impetus recently to develop advanced thermochemical processes such as pyrolysis and gasification to treat biomass and municipal solid waste (including refuse-derived fuel therefrom). This is because these processes have the potential to add value to cheap and abundant materials by converting them into advanced biofuels and chemicals. The work presented in this paper is concerned principally with the technical analysis and review of new-generation, state-of-the-art systems based on fluidised bed reactors operated with biomass and solid waste. A comprehensive assessment of fluidised bed reactor types and operations is considered, with particular attention given to those processes aimed at the production of clean syngas for the subsequent synthesis of high-value products, including bio-hydrogen, synthetic natural gas (SNG), and liquid fuels.

Keywords: fluidised beds, waste, thermochemical processes, waste-to-fuels

1. Introduction

Biomass and municipal solid waste (MSW) feedstocks arise in vast quantities, presenting a largely untapped resource. Harnessing the energy content of these feedstocks—a significant portion of which will be renewable—offers significant environmental, economic and, indeed, societal benefits. While mass burning, for heat and/or power generation, has been the traditional route, thermochemical methods including gasification and pyrolysis open up a range of options from chemicals to synthetic natural gas and transport fuels (Barbuzza et al., 2019). This is becoming increasingly relevant given the drive to find alternatives to fossil fuels and reduce CO_2 emissions (Masnadi et al., 2015).

Thermochemical processes have been known and used for centuries. Examples include the pyrolysis and gasification of coal as early as the 19th century (Kamble et al., 2019; Nie et al., 2017). The pyrolysis of coal produced coke and a coal gas, while the gasification of coal produced a combustible gas referred to as synthetic gas (syngas), or producer gas. In spite of this long history, the development of thermochemical technologies for processing biomass and waste materials has been relatively recent, driven by the demand for resource conservation and more efficient energy recovery. In terms of feedstock handled by gasification plants worldwide, for example, biomass and waste represent a very small portion, with most synthesis gas production derived from fossil sources. Notwithstanding this, the thermochemical treatment of residual biomass, including solid waste, has significant potential in its own right. In this respect, they add value to low- or negative-value feedstock by converting them to marketable fuels and products (Materazzi and Lettieri, 2017). Furthermore, while waste materials can present challenges, they have certain economic benefits over other biomass. For instance, most waste sources are subject to a gate fee for their disposal; collection systems tend to be established, the cost of which is normally incurred by the waste producer. Finally, unlike certain biomass materials, waste does not compete with the production of food (Matsakas et al., 2017).

Fluidised beds have historically been used in the thermal processing of solid fuels due to their flexibility and good conversion efficiency. Today, they still offer good prospects for a rapid deployment of new-generation

thermochemical treatments for advanced biofuel production. This review focuses on the application of fluidised beds for a range of different thermochemical routes for the conversion of waste biomass and MSW-derived feedstock into energy, gases or liquid fuels. A thorough assessment of fluidised bed reactor types and operational process conditions is provided. Technologies aimed at the production of clean syngas are given special attention, keeping in mind the high value products generated, including bio-hydrogen, biosynthetic natural gas (bioSNG), and liquid fuels.

2. Basics of thermochemical conversions

Thermochemical conversion technologies are used to transform wastes and biomass into commercial fuels and energy by employing processes at high temperatures. They include combustion or incineration, pyrolysis, gasification, and may include additional chemical processes for the final fuel synthesis. Apart from other technological features, the temperature and excess air quantity differentiate these thermochemical routes. Consequently, they may generate CO_2 and water as final products (maximum generation of heat) or intermediate valuable products (mostly hydrocarbons and syngas). Gasification and pyrolysis are not new concepts; however, only in recent years they have been applied to the treatment of solid materials (Materazzi, 2017). These processes can also be employed to produce syngas (namely H_2 and CO) for use in the production of modern synthetic fuels (e.g. biodiesel, ethanol, bio-syngas or bio-hydrogen). These fuels can then be converted into electricity or heat, or used for transportation.

A number of exothermic and endothermic chemical reactions are involved in the thermochemical processing of waste residues. The most important ones are listed in

Table 1. The prevalence of one over the other defines the overall process conditions and the final product composition.

2.1 Combustion

Combustion represents perhaps the oldest utilization of solid fuels in thermochemical processes. Chemically, combustion is the complete oxidation of the hydrocarbon species in biomass or wastes, and conversion into mainly H_2O and CO_2. Combustion involves several processes which occur simultaneously. Initially, the moisture content is driven off by the heat in the combustion chamber (or boiler), followed by the release of its volatiles content (referred to as devolatilisation). Actual combustion only commences once the volatiles are ignited in the presence of air. The heat released is used to produce a high-pressure steam for electricity generation in steam turbines, and low-pressure steam for internal use. Although bottom and fly ashes (derived from the inorganic content of the waste) play a small role in the overall process, they have a significant effect on the energy balance, by way of the mean heat capacity (Materazzi et al., 2013). Incidentally, ferrous and non-ferrous metals may also be recovered depending on the bottom ash treatment options. Furthermore, the residual ash can be improved, enabling its use as a construction material (Teixeira et al., 2019).

2.2 Pyrolysis

Pyrolysis takes place in the total absence of oxygen, except in cases where partial combustion is needed to provide the heat for the process itself. During the pyrolysis of solid waste fuel, decomposition occurs at relatively low temperatures (approx. 300 °C–600 °C (Kwon et al., 2019)). The biomass or waste feedstock is converted into gaseous (syngas), solid (char) and liquid (tar) products.

Table 1 Main reactions during the thermochemical transformation of solid fuel.

Type/Label	Reactions	Energy	Equation
Exothermic		kJ/mol	
Combustion	{volatiles/char} + O_2 → CO_2 + H_2O	−300–400	(1)
Partial oxidation	{volatiles/char} + O_2 → CO + H_2	−100–200	(2)
Methanation	{volatiles/char} + H_2 → CH_4	−74.9	(3)
Water-gas shift	CO + H_2O ↔ CO_2 + H_2	−40.9	(4)
CO methanation	CO + $3H_2$ → CH_4 + H_2O	−206.3	(5)
Endothermic			
Pyrolysis	Biomass/waste → volatiles + char	—	(6)
Water-gas/steam-carbon	{volatiles/char} + H_2O → CO + H_2	159.9	(7)
Boudouard	{volatiles/char} + CO_2 → 2CO	172	(8)

The net calorific value of the syngas is typically in the range of 10–20 MJ/Nm^3. The condensable fraction is recovered by cooling the syngas for use as a liquid fuel. The rate of heating and the pyrolysis temperature affect the proportion of useful product generated from the process (namely H_2, CO, CH_4 and other hydrocarbons) (Safdari et al., 2019). The liquid product is referred to as bio-oil and can be used as an alternative fuel oil in power and heat applications or as feedstock in the production of various commodity chemicals. The major drawback concerning bio-oil is its high oxygen content (35–60 wt%) (Uzoejinwa et al., 2018), which results in a low calorific value, instability and corrosiveness of the fuel (Sharifzadeh et al., 2019). The lower heating value (LHV) is usually between 18 MJ/kg and 20 MJ/kg, which is lower than the LHV of conventional liquid fuels such as diesel (42 MJ/kg) and gasoline (44 MJ/kg) (Perkins et al., 2018). Recently, different studies to solve this issue have been conducted on the co-pyrolysis of biomass and waste plastics. These substances are particularly attractive for their high hydrogen contents of about 14 wt% (e.g. polyethylene, polypropylene, polystyrene), hence they could donate hydrogen during the process with biomass and improve the bio-oil quality (Zhou et al., 2006). According to Brebu et al. (2010), the calorific value of the fuel oil produced via the co-pyrolysis of wood chips with polypropylene (at 1:1 mixing ratio) is 45 MJ/kg. This value is much higher than that obtained from wood chips alone (at 19.9 MJ/kg).

2.3 Gasification

Gasification is an intermediate between combustion and pyrolysis, involving partial oxidation of the fuel. In particular, the oxygen is added but the amount is not sufficient to allow the fuel to be completely oxidised (i.e. sub-stoichiometric), at temperatures typically above 800 °C (Almeida et al., 2019). The products of gasification consist of partially oxidised compounds—mainly H_2, CO and CO_2. Partial combustion or an external heat supply are necessary to sustain the gasification process. The main product is a syngas which contains hydrogen, carbon monoxide and methane with a net calorific value of 4–10 MJ/Nm^3 (Materazzi et al. 2016). This high calorific value means that the gases from gasification can be used in gas turbines and/or internal combustion engines, or burned in conventional boilers connected to steam turbines. With regard to energy production, gasification has many advantages over combustion. For instance, the syngas product may be more valuable as it can be combusted at higher temperatures or used in fuel cells (Safarian et al., 2019; Whitty et al., 2008). It also produces a solid ash product, low in carbon (i.e. char) and other inorganic contaminants (for example, chlorides, sulphides, heavy metals, etc.). The biggest potential of waste and biomass

gasification, however, is still not fully realised. Once the syngas gas is cleaned and all impurities removed, it can be used to generate chemicals or high-quality fuels via catalytic stages (e.g. Fischer-Tropsch, methanation, etc.) (Karl and Pröll, 2018). This opens the door to a new and potentially outstanding biorefinery industry which sees gasification as one of the most promising thermochemical technologies in the future for the production of sustainable fuels (Mazaheri et al., 2019).

3. Fluidised bed technologies applied to thermal treatments

Fluidised bed reactors (FBR) have a long record of success in the field of thermochemical conversion due to their favourable mixing features, near-constant temperatures and the good operating flexibility (Salatino and Solimene, 2017). These features make fluidised beds particularly suitable for the application with heterogeneous feedstock, including biomass and waste (Siedlecki et al., 2011).

In a fluidised bed, the fuel is suspended in a swirling mass of hot particles (such as sand), fluidised by an updraft of hot gases. This system facilitates thorough mixing, and therefore good mass and heat transfer. These are the main reasons why fluidised beds are best suited to transform heterogeneous materials via thermochemical processes. The exit gases carry off some particulates of ash, fines and bed material. Heavier bed particles and ash are decanted from the base of the gasifier, and replaced with fresh bed material (normally inert sand) (Materazzi, 2017). This mechanism is fuel-dependent, as fuels with a higher ash content require more frequent extractions. In modern applications, fluidised bed plants are better suited to treating refuse-derived fuel (RDF) than raw MSW. This requires pretreatment of the waste feedstock to remove recyclable materials, as well as dense, coarse objects, and to reduce particle size. Fluidised beds offer flexibility in terms of feedstock calorific value, moisture, particle size and density and sulphur content. Nonetheless, limitations may arise if the feed contains a significant portion of large, dense particles or low-melting-point ash. This flexibility centres on the ability to mix and hold the fuel within the fluid bed, providing a sufficient residence time for reactions to reach completion. Alkaline materials (for example, limestone) can also be charged to the bed to help retain acidic impurities or to aid tar cracking and reforming reactions (Schmid et al., 2018). Worthy of note is that the heat input from the burning char (within the bed) and the devolatilised gases (above bed) balances the outgoing heat 'consumed' by endothermic reactions in the gas phase (e.g. water-gas/steam-carbon, steam reforming, etc.) (as illustrated in **Fig. 1**). This provides the basis for controlling the temperature of the bed during steady-state
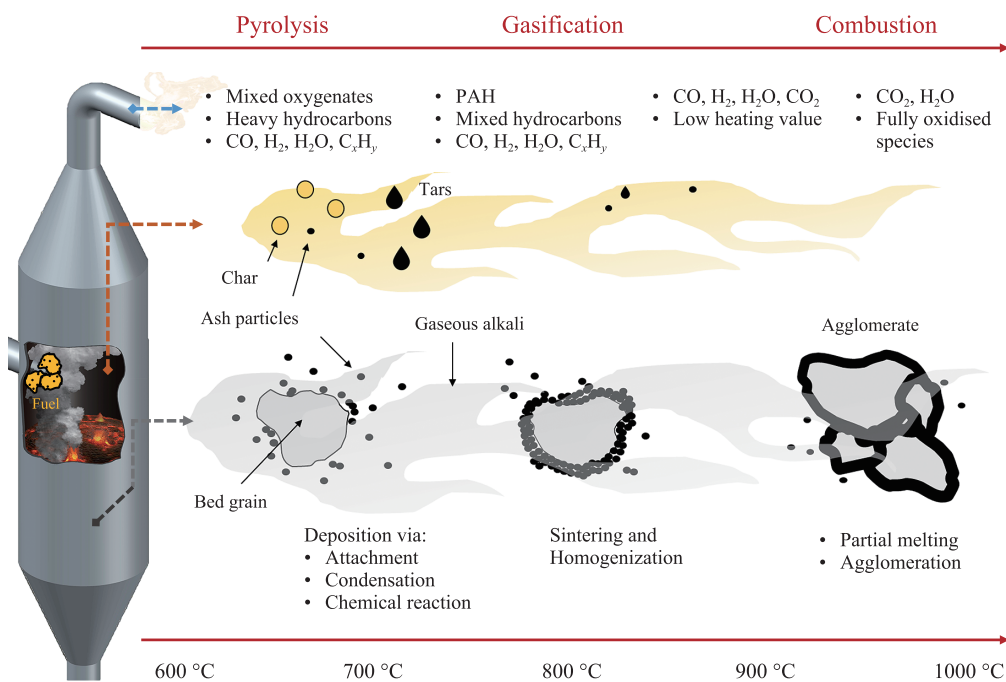
Fig. 1 Fuel transformation scheme and influence of temperature and oxidation stage in an FBR.
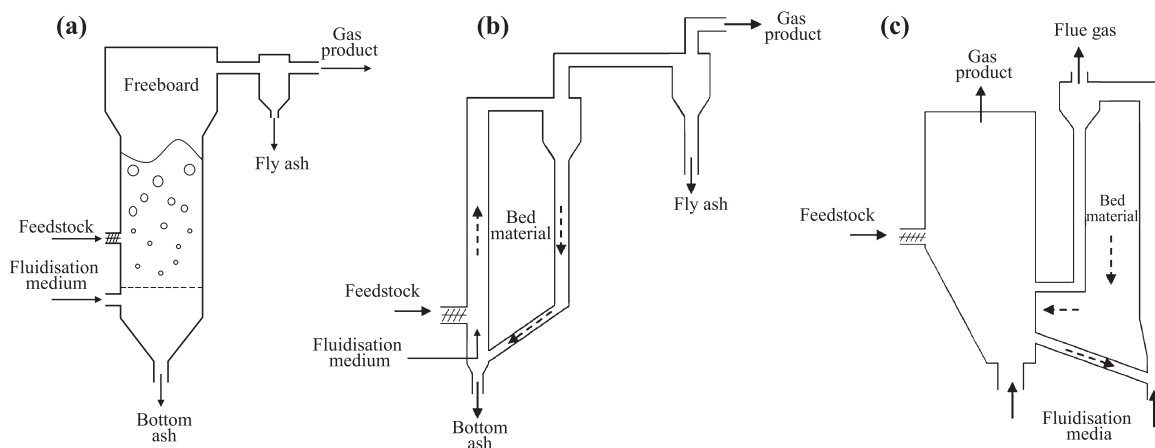

Fig. 2 Fluidised bed reactor configurations: **(a)** bubbling; **(b)** circulating; **(c)** dual. Source: Adapted from Motta et al. (2018).

operation. In this respect, the equivalence ratio (ER) (namely the amount of air/oxygen inputted relative to that required for stoichiometric combustion) is the parameter that determines the difference between combustion, pyrolysis and gasification (Materazzi et al., 2013).

Fluidised bed technology is also well proven and mature in other applications such as the combustion of pulverised coal and biomass (Materazzi and Lettieri, 2017). Different technologies can be classified in accordance with their physical configuration and operating conditions (**Fig. 2**), as described in the following sections (Motta et al., 2018).

3.1 Bubbling fluidised bed reactor

Inside a bubbling fluidised bed reactor (BFB), the bed media is fluidised from the bottom of the bed by way of a distribution plate or gas nozzles with a velocity varying in a range of 1 and 3 m/s (Molino et al., 2016). Under these conditions, the bed material (particle diameters ranging between 0.5 and 1.0 mm, Group B of Geldart classification) is fully fluidised and behaves like a boiling liquid (Kunii and Levenspiel, 1991). The fluidisation state is maintained by a gas-bubble emulsion which continuously agitates the solid phase, enabling good mass and heat transfer between the solid and gas phase. Within the upper part of the reactor, namely the freeboard, only the gas phase is present, as the bed material does not normally get carried this high. Some of the gas-phase reactions take place here, even though the main stages of thermochemical conversion occur within or just above the fluidised bed (Molino et al., 2016). The cross-sectional area of the

freeboard is usually wider in order to decrease the superficial velocity of the gas, maintain a fixed solid quantity in the bed, and compel the particles to return to the bed. At the gas outlet, appropriate equipment is required (e.g. cyclones) in order to capture particulate matter (e.g. fly ash) formed during the process (Motta et al., 2018). Concerning the feedstock, BFBs present good flexibility and are able to process a broad variety of fuels. Typical feedstocks include biomass, RDF, low-rank coals, lignite, plastics and solid-recovered fuels (SRFs), with particle sizes below 6 mm (Arena et al., 2011; Arena and Di Gregorio, 2016; Hu et al., 2012; Ud et al., 2016). Valin et al. (2019) have compared the results obtained from the air gasification of woody biomass (namely beech sawdust and waste wood) and solid-recovered fuel using a bubbling fluidised bed at 1.5 bar. The experiments were carried out while varying the addition of steam, ER ratio (between 0.00 (pyrolysis conditions) and 0.34) and the temperature (between 800 and 900 °C). They obtained a cold gas efficiency and carbon-gas conversion of 59 % and 80 %, respectively for SRF, and 75 % and 92 % for beechwood. The authors concluded that the co-gasification of SRF and biomass might be an effective way to improve the overall efficiency and also limit the pollutant content in the final product. In order to inhibit the phenomena of bed particle agglomeration, which leads to defluidisation of the bed, BFB reactors should operate at temperatures lower than the fuel's ash melting temperature (Samiran et al., 2016). Zhu et al. (2019) studied the co-gasification of polyethylene and beech wood in a lab-scale fluidised bed reactor. In particular, they investigated the effect of steam injection, feedstock composition and bed material on the hydrogen production. The results show that the Na-Y zeolite provides the highest hydrogen content in the products among all bed materials tested, including sand, ZSM-5 zeolite, and FCC catalysts. Moreover, the authors found that the smaller the wood-to-PE ratio, the higher is the hydrogen production.

The use of stand-alone BFBs is limited for some syngas applications (i.e. catalytic transformation), due to both the low gasification efficiency and solid conversion (Ramos et al., 2018). Such restrictions can nonetheless be prevented by providing a longer solid residence time (for example, through a solid circulating loop, as used in circulating fluidised beds) (Basu, 2006), or by adding an additional reforming step (e.g. plasma reformer) (Materazzi et al., 2015).

3.2 Circulating fluidised bed reactor

Circulating fluidised bed (CFB) or external circulating fluidised bed (ECFB) reactors can maintain the gas superficial velocities up to three to five times (5–10 m/s) longer than the bubbling arrangement (Molino et al., 2016). Char

and bed particles become entrained in the gas stream as a result, increasing the amount of solids in the freeboard. A downstream unit is thus required to separate (e.g. using a cyclone) and recirculate these particles (Ahmad et al., 2016; Alauddin et al., 2010). Recycling the solids has the advantage of increasing the particle residence time, which improves the carbon conversion efficiency and reaction rates and leads to lower tar production (Gómez-Barea and Leckner, 2010; Puig-Arnavat et al., 2012; Samiran et al., 2016). The bed material is normally the same as for BFBs, but with a smaller diameter (e.g. 0.2–0.5 mm). Similar to BFB reactors, CFBs are able to operate with different types of feedstock, as shown by Duanguppama et al. (2016). The authors studied the pyrolysis of sawdust contaminated with mineral oils and solid wastes. In particular, they demonstrated that the bio-oil achieved its maximum yield of 67 wt% at 500 °C, with an LHV of about 30 MJ/kg. Furthermore, they found that the presence of minerals increased the calorific value and the non-condensable gas content by nearly 300 %.

There are some disadvantages to this configuration, including process control as well as higher investment costs (associated to solids separation equipment) (Zhou et al., 2009). Similar to BFBs, limitations are also present with respect to bed agglomeration and ash melting (Hofbauer and Materazzi, 2019), especially when operated on waste materials.

3.3 Dual fluidised bed reactor

Dual or internal circulating fluidised beds (DFB or ICFB, respectively) consist of two interconnected fluidised bed reactors with the bed material circulating between them, enabling efficient mass and heat transfer between the two units (**Fig. 3**). The solid fuel is charged to the 'fuel reactor' where it undergoes gasification or pyrolysis. The generated char and unreacted fuel are
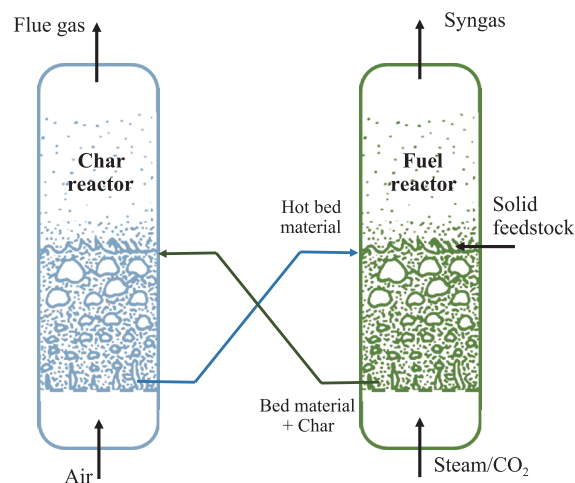

Fig. 3 Concept of DFB fuel conversion.

subsequently transported into the so-called 'char reactor' for full gasification or combustion. In this way, the conversion processes are decoupled, ensuring complete independence of the gas phase in the two vessels. This results in a purer and higher-quality gas product than that from single reactors (Fuchs et al., 2019).

In gasification systems, the fuel reactor is a bubbling fluidised bed gasifier operating between 800 °C and 850 °C with steam as the gasification medium (i.e. steam gasification). Since the reactions during the steam gasification are mostly endothermic (e.g. Eqn. (7), **Table 1**), heat must be generated and provided to this stage (Shen et al., 2008). The heat required is generated in the second reactor (fluidised with air), where combustion of the residual char from the gasification section takes place at 900–950 °C (Fuchs et al., 2019). The flue gases generated exit the char combustion reactor separately from the produced syngas, which is therefore free of air/nitrogen. Concurrently, the heated bed material is recirculated into the gasification reactor, acting as an external heat source (La Villetta et al., 2017).

DFBs present good scale-up potential and are suitable for high specific capacities, although their construction is rather complex (Puig-Arnavat et al., 2010). As for most fluidised bed systems, these reactors can process a broad variety of biomass including sewage sludge, grass (Van der Drift et al., 2005), wood chips and pellets (Hofbauer and Rauch, 2008), dried coffee grounds (Xu et al., 2006), cedar, oak sawdust (Suzuki and Namioka, 2005), almond shells and waste residues (RDF, SRF, mixed plastics, etc.) (Corella et al., 2007). Furthermore, dual fluidised bed systems generate syngas with a reasonable calorific value, rich in hydrogen. In this respect, Benedikt et al. (2018) carried out a set of experiments using different types of biogenic fuels (i.e. sugar cane bagasse, softwood, olive pomace, bark and rice husk) and waste-derived fuels (i.e. MSW fraction, shredder light fraction and MSW fraction with 25 % blending of lignite) in a 100-kW pilot plant at TU Wien, Austria. The resulting product gas has a LHV of around 11–12.5 MJ/Nm^3 for the gasification of biogenic feedstock, and 14–16 MJ/Nm^3 for that of waste. Moreover, the H_2/CO ratio of the syngas reached a value up to 3.9 for the waste-derived fuels (Benedikt et al., 2018). A larger plant of 20 MW$_{fuel}$ based on the DFB concept is located in Göteborg, Sweden (Leckner, 2016) for the production of bioSNG from biomass.

A range of different design options can be considered for DFBs. This includes, for instance, two fast fluidised beds, a bubbling and a fast fluidised bed, or a combination of two bubbling fluidised beds (Fuchs et al., 2019; Kunii and Levenspiel, 1991; Paisley and Overend, 2002). An example of a design based on the ICFB principle is the MILENA gasification process (**Fig. 4**).

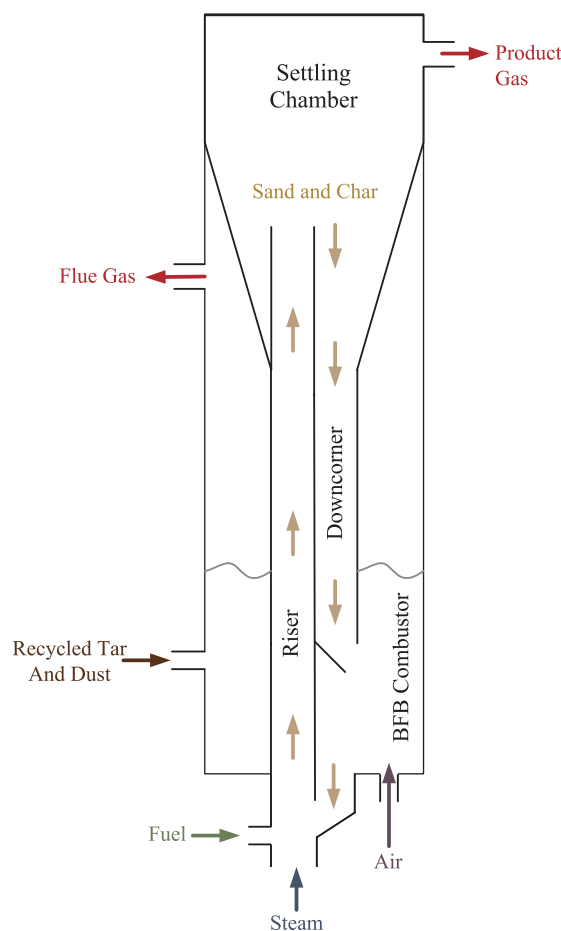The gasification section includes a downcomer, riser

Fig. 4 Lab-scale MILENA gasifier. Source: Adapted from Van der Meijden et al. (2010).

and settling chamber, whilst the combustion section encloses a sand transport zone and the BFB. The biomass is fed into the riser where a small quantity of superheated steam is inputted from below (5 wt% of the biomass input) (Van der Meijden et al., 2010). In the riser, opposite and below the biomass feeding point, an orifice allows the entrance of the hot bed material (typically olivine or sand) from the combustor. The hot bed material serves as a heating source for the biomass, which reaches a temperature of 850 °C. The heated fuel particles devolatilise and are converted into char, tar and gas, which rises through the reactor with a vertical velocity of nearly 6 m/s (Van der Meijden et al., 2010). This leads to a turbulent fluidisation regime within the riser as well as significant entrainment of char and bed material. Since the vertical velocity decreases in the settling chamber, the gas separates from the solids, which fall down into the downcomer. The product gas exits from the top and is sent to the cooling and cleaning section. The char is oxidised with air in the bubbling fluidised combustor in order to heat the bed material up to 925 °C. Subsequently, it leaves the combustion section from the bottom and is sent to the riser again. The product syngas contains a certain number

of contaminants such as sulphur, chloride, tar and dust (Van der Meijden et al., 2010). These species must be removed in order to prevent poisoning the catalyst in later syngas applications (e.g. bioSNG synthesis). A pilot plant of MILENA gasification (500 kW) is employed by the Energy Research Centre in the Netherlands (ECN), using wood pellets as feedstock (Han et al., 2018). Operating in the temperature range of 830–870 °C (gasification) and 940–1050 °C (combustion), the system can achieve a syngas with an H_2 concentration on a dry basis of 23.8-vol% and a high heating value (HHV) of 15–17 MJ/Nm³.

Similarly to DFB gasification, pyrolysis can also be decoupled into two separate reactors, namely fuel pyrolysis and char conversion. This is also known as pyrolysis-based cogeneration (Han et al., 2018). This kind of configuration is still largely applied in the pyrolysis of coal, lignite and bituminous material (Han et al., 2018). More research is needed on biomass and waste as feedstock. Aho et al. (2010) conducted an experimental study on the pyrolysis of pine wood with subsequent improvement of pyrolysis vapours in a dual fluidised bed reactor. The temperatures of the pyrolysis and upgrading steps were 400 and 450 °C, respectively, with iron-modified zeolites used as catalysts. They found that the yield of bio-oil could reach 52.7 wt% and that a high selectivity through de-oxygenated compounds could be achieved. Similar configurations have been used recently to recover waste plastics in the UK and transform these into a reusable wax precursor for upgrading to fuels and new materials.

3.4 Chemical looping

Chemical looping gasification (CLG) and chemical looping combustion (CLC) represent two established and attractive carbon removal technologies which permit N_2-free syngas or CO_2 capture applications without requiring the energy-insensitive gas-gas separation step (Mattisson et al., 2018; Stollhof et al., 2018). As in DFB systems, chemical looping consists of two different reaction zones (**Fig. 5**): a fuel reactor in which gasification or combustion take place, concurrently with the reduction of the oxygen carrier material (Eqns. (9) and (10)); and an air reactor in which regeneration of the oxygen carrier occurs (Eqn. (11)). In this way, air and fuel are never mixed, resulting in a high-purity syngas or CO_2 stream available for carbon capture and storage (CCS) or utilization (CCSU).
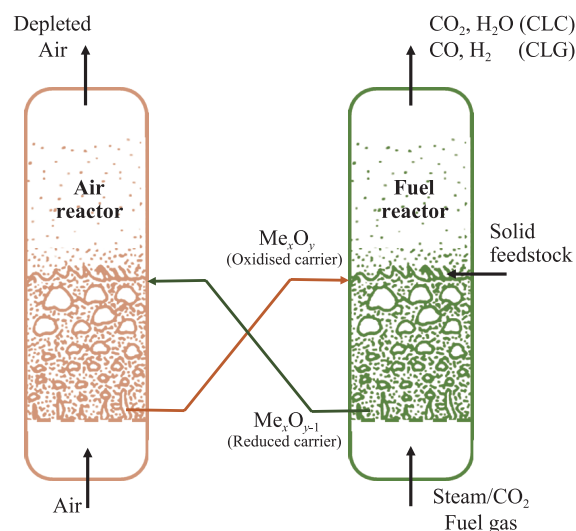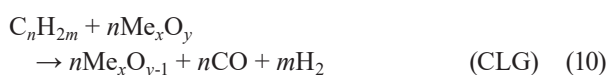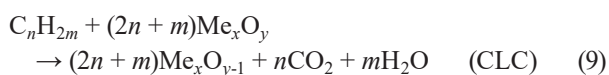
$$C_nH_{2m} + (2n + m)Me_xO_y \rightarrow (2n + m)Me_xO_{y-1} + nCO_2 + mH_2O \quad (CLC) \quad (9)$$

$$C_nH_{2m} + nMe_xO_y \rightarrow nMe_xO_{y-1} + nCO + mH_2 \quad (CLG) \quad (10)$$

Fig. 5 Concept of chemical looping in fluidised beds.

$$Me_xO_{y-1} + 1/2O_2 \rightarrow Me_xO_y \quad (11)$$

The oxygen carrier is typically a metal oxide powder, allowing the transport of O_2 from the air reactor to the fuel reactor (Pans et al., 2013). Good candidates are copper, manganese, iron, cobalt and nickel. Moreover, some authors have found that even iron in olivine (Lancee et al., 2014) and silica sand used as bed material (Udomsirichakorn et al., 2014) are also capable of transferring oxygen between the two reactors. For the majority of chemical looping concepts, the air and fuel reactors are designed as a high velocity riser and low velocity BFB, respectively (Han et al., 2018). Using heat provided by the oxygen carrier, the solid fuel decomposes into volatiles and char. The former species react directly with the oxygen content of the metal oxide, whilst the oxidation of char is a slow process that requires an intermediate steam gasification step (Han et al., 2018). A CLC system with biomass and an iron-based oxygen carrier was built in Nanjing, China, in 2010 (Lyngfelt, 2014). Results show that the smaller 1-kW plant generated an outlet gas from the fuel reactor with a carbon distribution of 95 % CO_2, 4 % CO and 1 % CH_4. Several CLC and CLG operations have been studied in small pilot plants (Lyngfelt, 2014). In this regard, it is important to recognise that the results obtained on a small scale cannot accurately indicate the performance on a large scale. This is due to the intrinsic differences between large and small fluidised beds (Lyngfelt and Linderholm, 2017). However, it has already been demonstrated that the CLC design is technically practicable for application on a large scale (Kolbitsch et al., 2009). Lyngfelt and Leckner (2015) presented an interesting techno-economic analysis for the effective scale-up of this technology up to 1000 MWth for solid fuels.

4. Effect of operating conditions

The importance of operating conditions in thermo-chemical processes have been extensively studied, and many excellent reviews can be found in the literature (Heidenreich and Foscolo, 2015; Hofbauer and Materazzi, 2019; Yates and Lettieri, 2016). This section will only highlight some of the key aspects related to operation of FBRs on waste feedstock. Among all factors, temperature is perhaps the most important. As shown in **Fig. 1**, FBRs usually operate at atmospheric pressure and relatively low temperatures (< 900 °C) in order to avoid sintering of the ashes and subsequent melting and agglomeration issues. This is particularly relevant to operations with waste feedstock, due to the high presence of ashes and inorganic components in these fuels (Yates and Lettieri, 2016). On the other hand, the amount of tar produced is known to increase with decreasing temperature (Kinoshita et al., 1994). The typical approach to avoid this inconvenience is to stage the oxidation phase at multiple levels, achieving high temperatures only when needed, i.e. in those areas where bed material is not present. These can include, for example, the freeboard in fluidised beds, or the entire gas space in dedicated 'thermal cracking' units. However, controlling the agglomeration phenomenon is also possible by means of frequent bed replacement and the addition of other components to the bed inventory. Lu et al. (2015) conducted a study on catalytic coal gasification in a pressurised fluidised bed reactor. They demonstrated that the sintering temperature of the coal ash increased from 650 °C to 740 °C by adding a small amount (5 wt%) of water-washed ash. The ash content in the fuel also affects the conversion process more directly. For instance, ash can cause a reduction in the char activity by hindering the reaction between oxygen and carbon within the pores. Furthermore, solids discharge rates in FBRs have to be enhanced significantly in order to keep a constant bed depth, thus increasing the fraction of heat losses and fluctuations within the system (Yates and Lettieri, 2016). Bed depth and fluidising velocity, in turn, have an influence on the residence time of reacting gases and particles within the reactor, therefore affecting the thermal conversion efficiency and gas composition. For example, an increase in bed height ensures a high residence time for the char particles within the bed and more stable conditions. On the other hand, the fluidisation velocity controls the mixing and the expansion of the bed, as well as the gas residence time and elutriation rates. Plenty of work has been conducted on different bed materials to be used in thermochemical processes, either for their catalytic properties in tar reforming, or for different retention capacities of inorganic contaminants (Heidenreich and Foscolo, 2015; Thunman et al., 2018). Koppatz et al. (2011) compared silica sand (as a reference inert material) and olivine in a pilot-scale DFB system for wood pellet gasification. The authors tested olivine with a particle size range of 400–600 μm and particle density of 2850 kg/m³. The results show a reduction of GC (Gas Chromatograph) tar and gravimetric tar content (both related to the fuel input) by about 30 % and 57 %, respectively. Ly et al. (2018) investigated dolomite with a particle size of 180–250 μm as a catalyst for bio-oil upgrading from tulip tree pyrolysis. They demonstrated that the HHV of the bio-oil reached a value between 23.09 and 28.1 MJ/kg, which was higher than that obtained from the pyrolysis with silica sand (i.e. 21.64–24.37 MJ/kg). In most cases, however, the extent to which solid particles affect the tar content and product composition is determined by a series of concurring elements, including feedstock composition and atmosphere in the reactor, rather than bed material alone.

5. State of the art of FBRs for thermochemical conversion

5.1 Fluidised bed combustion

Combustion currently represents the most well-established thermochemical conversion of waste into energy, with more than 1400 incineration plants in operation worldwide (Dong et al., 2018a,b; Leckner, 2015). There has been a progressive increase in the number of combustion plants in different parts of the world: in Europe 455 plants were in operation in 2012 (Lausselet et al., 2016), whereas the number in China has risen from 54 plants in 2004 to 188 in 2014 (Dong et al., 2018a). Even though the last generation of MSW combustors employs effective and advanced flue gas cleaning, ash recycling and the use of combined heat and power (CHP) cycle, there are still some limitations concerning electricity efficiency—which is low at about 22–25 % (Dong et al., 2018b; Panepinto et al. 2014). This is due to a restriction on the maximum steam temperature of the boiler, which is typically kept below 450 °C to avoid corrosion by HCl (Belgiorno et al., 2003). Although fluidised bed reactors are a promising technology, currently the main combustion technologies for MSW treatment remain moving-grate and rotary kiln combustors (Materazzi and Lettieri, 2017). Moving grates are employed in most of these applications and have been fully developed in order to meet the demands for large-scale performance. This is due to their ability to handle large volumes of waste, avoiding the need for prior removal of bulky material through shredding and sorting (Wissing et al., 2017). The percentage of MSW combustion plants utilising moving grates is 94 %, 88 %, 85 % and 76 % in Germany, EU, France and US, respectively, with the remaining plants being either rotary kiln or fluidised bed combustors (Lu et al., 2017). However, the

Table 2 Fluidised bed combustion systems. Source: Adapted from Koornneef et al. (2007)

Organisation	Technology	Capacity (MWe)		No. of Installations (2007)
		Min	Max	
Alstom	BFB	17	142	7
	CFB	2	520	51
Babcock and Wilcox	CFB	3	76	22
Babcock Borsig	BFB	0	35	5
	CFB	9	120	10
Bharat Heavy Electricals	BFB	5	50	18
Outotec	BFB	10	45	9
Foster Wheeler	BFB	0	117	51
	CFB	0	460	161
Kvaerner Pulping	BFB	6	117	56
	CFB	0	240	32
Lurgi	CFB	9	225	35

major downside of moving grates is their higher relative maintenance and investment costs as compared to the other two technologies.

Fluidised bed combustors, on the other hand, can only process waste after shredding and size reduction (such as RDF). Nevertheless, they can operate on a broad variety of waste feedstock, in terms of properties and controlling emissions (Materazzi and Lettieri, 2017). Another important advantage is that the capital and operational investment for fluidised beds is only approx. 70 % of that for moving grates (Makarichi et al., 2018). Nowadays, even though China has the largest capacity of MSW plants operating fluidised beds, most of this technology is still imported from Europe (Li et al., 2015; Lu et al., 2017). The largest suppliers of fluidised bed combustors are shown in **Table 2**. The largest suppliers of CFB technology are Alstom and Foster Wheeler, with Kvaerner being the market leader for BFBs. Outotec (formerly EPI) and Bharat Heavy Electricals are prominent in their local markets of North America and India, respectively. A number of Outotec's BFB RDF combustors, however, have been operating successfully in Italy (Materazzi and Lettieri, 2017).

Recent combustor technologies comply with environmental requirements, but potential risks concerning some toxic compounds released from the gas (i.e. dioxins and furans) or from the ashes (heavy metals) are still present at the core of public debate. In this regard, the development of alternative and more environmentally friendly waste treatment is still essential.

5.2 Fluidised bed pyrolysis

Pyrolysis has been studied as an effective alternative to combustion for MSW disposal that allows more effective resource and energy recovery. There is an abundance of renewable feedstocks available worldwide that can be converted into biofuels via pyrolysis. This includes forestry materials, agricultural crops, algal biomass and, more generally, lignocellulosic biomass (Dhyani and Bhaskar, 2018). Furthermore, several studies have been conducted on different industrial wastes (such as sewage sludge, plastics and tyres), while only in the last few years pyrolysis has been commercialised to treat MSW. Indeed, the pyrolysis of MSW is receiving growing attention in both small and larger cities due to an increasing struggle to find new sites for landfills and incinerators, and consequently to avoid long-distance transportation (Chen et al., 2015). Although rotary kiln and fixed-bed reactors are used for MSW pyrolysis, fluidised bed reactors remain the main focus for research and future exploitation. In particular, they have been studied to investigate the behaviour of fast pyrolysis, as they offer higher heating rates (Hofbauer and Materazzi, 2019). Industries which have developed fast pyrolysis technologies for generating bio-oil from biomass using fluidised beds include Ensyn (Canada and USA), DynaMotive (Canada) and the VTT/Valmet/Fortum consortium (Finland) (Perkins et al., 2018). A summary of the commercial pyrolysis plants worldwide is shown in **Table 3**.

DynaMotive's fast pyrolysis process was developed at the University of Waterloo in Canada from pyrolysis experiments on wood. The process produces bio-oil (50–75 wt%), non-condensable gases (10–20 wt%) and char

Table 3 Pyrolysis units worldwide using fluidised bed reactors. Source: Adapted from Dhyani and Bhaskar (2018) and Perkins, Bhaskar, and Konarova (2018)

Organisation	Location	Technology	Feed rate (tpd)	Status
RTI International	USA	BFB	1	Operational
Ensyn	Canada	CFB	2	Operational
Red Arrow	USA	CFB	3	—
Union Fenosa	Spain	FB	5	Shutdown
University of Waterloo	Canada	BFB	6	—
DynaMotive	Canada	BFB	11	—
Valmet	Finland	CFB	15	Operational
ENEL	Italy	CFB	16	—
Red Arrow	USA	CFB	24	—
Red Arrow	USA	CFB	30	—
Ensyn	Canada	CFB	150	Operational
Fortum	Finland	CFB	274	Operational
UDT	Chile	FB	0.36	Operational
University of Science & Technology of China, Hefei	China	FB	2.88	Operational
Metso	Finland	FB	7.2	Operational
Biomass Engineering Ltd.	UK	FB	10	Upgrade
Recycling Technologies	UK	FB	25	Operational
Iowa State University	USA	FB	0.24	Operational
National Renewable Energy Laboratory	USA	FB	0.3	Operational
UOP	USA	CFB	1	Construction
Virginia Tech	USA	FB	6	Operational

(15–20 wt%) which is combusted in order to provide heat to the fluidised bed, maintaining it at the desired operational temperature of 430 °C (Perkins et al., 2018). The relative amount of each product depends on the feedstock being processed. Ensyn's rapid thermal processing (RTP) technology was developed at the University of Western Ontario, in Canada, stemming from research to produce chemicals from biomass (Venderbosch, 2015). The core of the process is a circulating fluidised bed reactor and the liquid yields vary between 65 wt% and 75 wt%. The first system was commercialised in 1982 and a demonstration plant of 15 tpd was sold to ENEL in Italy. At present, there are four plants in operation in Ontario with a capacity of about 11 million l/y of pyrolysis oil produced. A number of plants with a capacity of around 350 tpd are under design and construction (Perkins et al., 2018). In 2009, Valmet built a bio-oil pilot plant (production capacity of 7 tpd) at their R&D centre in Tampere, Finland. A large-scale plant (capacity 50,000 tpa of bio-oil) was subsequently built into Fortum's combined heat and power plant in Joensuu, Finland, in 2013. The liquid product has an LHV of 13–18 MJ/kg and it is obtained from sawdust,

wood chips and forest residue. Both pilot and commercial pyrolysis systems are presently operational and integrated with a circulating fluidised bed reactor.

With regards to the pyrolysis of polymer feedstock, fluidised bed reactors can have advantages over other reactors due to favourable heat transfer during cracking (Chen et al., 2015). Hence, there are various processes which use pyrolysis for the treatment of mixed plastic waste (MPW) such as the BP polymer cracking process (Al-Salem et al., 2010) and the Hamburg process (Kaminsky, 2006). The Recycling Technologies plant in the UK is an example of commercial-scale pyrolysis which is able to handle 9000 tpa of residual plastic waste (Recycling Technologies, 2019) to convert it into a reusable wax product. The DFB system consists of a fluidised bed pyrolyser containing bed material which is continuously circulated from/to the regenerating section. Within this module, the bed material is heated up to 850– 900°C by combustion of the lightest fraction (e.g. methane, ethane) from the distillation stage, and then recirculated to the first reactor where plastic pyrolysis occurs.

5.3 Fluidised bed gasification

Gasification is currently considered a more attractive process when compared to combustion and pyrolysis for both biomass and waste treatment, due to the wide choice of the various end products (Bhavanam and Sastry, 2011). Moreover, it represents a cleaner alternative solution with respect to increasing environmental restrictions (Arena, 2012). However, the gasification of problematic materials, such as waste, for biofuel production still needs to be proven on a large scale for commercial take-off. The design of commercial gasifiers, currently used for combined heat and power (CHP) production only, depends on feedstock availability, ranging from agricultural to industrial and municipal waste streams. As with pyrolysis, fluidised beds are the most employed for both waste and biomass treatment as they provide a robust and flexible technology, allowing a broad range of particle size feedstocks to be processed (Ramos et al., 2018).

A large-scale CHP gasification plant using a fluidised bed reactor is located at Lathi, Finland. It was developed by Foster Wheeler and has been operational since 2012 (Dong et al., 2018b). It has a capacity of 250,000 tpa of waste feedstock unsuitable for recycling, in the form of SRF. The plant achieves a CHP efficiency and a net electricity efficiency of 61 % and 27 %, respectively. Waste gasification takes place in a circulating fluidised bed reactor operated at 850–900 °C. As mentioned in Section 3.3, DFB reactors are also being studied increasingly for gasification. This type of reactor has been operated successfully since 2001 in Güssing, Austria; with wood chips as feedstock, olivine as bed material and operating at temperatures between 850 °C and 900 °C (Fuchs et al., 2019; Karl and Pröll, 2018). The thermal power input of the plant is 8 MW, employed in an electric gas engine of 2 MW. An important success was achieved in 2007 when an adsorption-enhanced reforming (AER) test was carried out on the Güssing system, demonstrating its feasibility even with a power plant engineered for conventional gasification (Fuchs et al., 2019). The effectiveness of an advanced gasifier concept, namely UNIQUE, has also been proven with the same plant (Heidenreich et al., 2016). UNIQUE consists of a compact solution based on the integration of fluidised bed gasification and gas cleaning and conditioning directly into one vessel reactor. This is achieved by adding sorbents to the bed, to promote primary tar reforming and the removal of inorganic compounds, and by installing catalytic filters in the freeboard, for combined secondary tar reduction and particulate removal.

As of 2004, Ebara Corporation had 21 processes operating commercially in Germany and Japan. The technology is based on twin internally circulating fluidised bed gasifiers. It was designed incorporating ash vitrification technology for the detoxification of waste, energy recovery and material recycling within an integrated and economical process. A large-capacity plant located in Aomori, Japan, has been in operation since 2000, and is based on gasification and slagging combustion. The process is able to handle 450 tpd of automotive shredder residues (ASR) and sewage sludge, with a power output of 17.8 MWe (TwE, 2013). More recent information on Ebara technology could not be found by the authors.

High-pressure operation in fluidised beds is also possible to favour the direct production of light hydrocarbons, including methane, in the syngas. A well-proven example of this is the high-temperature Winkler process (also known as HTW). The process is an evolution of the early steam/oxygen coal gasifier patented by Winkler in 1922, further developed in 1997 for applications in power generation and the production of methanol (Leckner, 2016). More recently (in 2011), Thyssen-Krupp-Uhde, Germany, commercialised the technology. One of their projects involves the production of methanol from syngas, after biomass gasification. The HTW gasifier employed, located in Sweden, has a capacity of 111 MW (Leckner, 2016). Another proven process which employs the HTW technology co-fires pure biomass with waste-derived fuels under pressure (at 30 bar). This enables a methane-in-syngas level of 8 % (dry basis) to be achieved (Adlhoch et al., 2000). A summary of other available gasification systems across the world using fluidised bed technologies is presented in **Table 4**.

6. Fluidised bed reactors for biofuel synthesis

The role of fluidised bed reactors as applied to the thermal treatment of solid feedstock has been described in the previous sections. However, these technologies also have significant potential with regard to other processes in the thermochemical industry. For instance, in recent years many authors have been studying a range of techniques for the production of biofuels using fluidised beds, including biosubstitute natural gas (bioSNG), biohydrogen and other chemicals.

6.1 Biohydrogen production

Producing hydrogen from biomass and waste can be an interesting and environmentally friendly solution for use in district heating and transport sectors (Heidenreich et al., 2016). Although there are many methods to produce hydrogen, those most commonly used are based on fossil fuel reforming. For instance, 95 % of H_2 production in the US is by way of the steam reforming of methane (Muradov, 2017).

Obtaining a hydrogen-rich syngas from gasification is a

Table 4 Gasification systems worldwide using fluidised bed reactors.

Location	Feedstock	Capacity	Technology	Name/Organisation
China	Agricultural and forestry residues	1 MW	FB	—/Tianyan Ltd.
China	Agricultural and forestry residues	0.2–1.2 MW	CFB	—/GIEC
China	Rice husk, straw, wood sawdust, peanut hulls	5.5 MW	CFB	—/GIEC
Austrian Energy, TU Vienna	Biomass chips	8 MW$_{th}$ [a]	BFB/CFB	Güssing FICFB/—
ECN Netherlands	Beechwood chips	0.03 MW$_{th}$ [a]	CFB/BFB	Milena/—
ECN Netherlands	Wood pellets	0.8 MW$_{th}$ [a]	CFB/BFB	Milena/—
GoBiGas, Sweden	Wood pellets	2 MW$_{th}$ [a]	BFB/CFB	Chalmers/—
Mid Sweden University	Wood pellets	0.15 MW$_{th}$ [a]	BFB/CFB	MIUN/—
Vermont, USA	—	90 MW$_{th}$ [a]	CFB/CFB	FERCO/—
University of Canterbury, New Zealand	Wood chips/pellets	0.1 MW$_{th}$ [a]	BFB/CFB	CAPE FICFB Gasifier/—
Trisaia, Italy	Almond shells biomass	0.5 MW$_{th}$ [a]	BFB/CFB	The JOULE-MFCF PlantENEA
Swindon, UK	RDF/wood chips	5 MW$_{th}$	BFB/Plasma	GoGreenGas
Edmonton, Canada	MSW	38 MLPY (methanol, ethanol)	BFB	Enerkem

Note: (a) Capacity as fuel input

fundamental step in ensuring a high-quality product. In particular, it is important that the syngas is free of nitrogen due to the difficulty in separating different gas components (Materazzi et al., 2018). This can be achieved by means of the polygeneration concept based on a dual fluidised bed configuration in which the steam gasification of biomass takes place (Kraussler et al., 2018). In this regard, Kraussler et al. (2018) obtained a practically nitrogen-free syngas with an H_2 concentration of 40 vol% using wood chips as the feedstock. Other valuable products obtained from the process were heat and electricity. Hydrogen can also be produced within fluidised bed reactors using different pathways such as methanol steam reforming. A study conducted by Shi et al. (2013) demonstrated that an FBR filled with $Cu/ZnO/Al_2O_3$ catalysts was capable of reaching a methanol conversion rate much higher than that of a fixed bed (over 20 %)—equating to approx. 91.95 % at 330 °C. This was due to the longer contact time between the reactants, a larger surface volume ratio and more uniform temperature. Alternatively, methanol can be partially oxidised using N_2O over an iron-chromium catalyst, achieving a yield of H_2 up to 95 % at 350 °C (Żukowski and Berkowicz, 2017). These routes are particularly advantageous if methanol can be obtained via biologic routes.

6.2 BioSNG production

Synthetic natural gas (SNG) produced from biogenic sources represents a renewable clean fuel substitute for fossil fuels in CHP, transportation and heating (Heidenreich et al., 2016). One of the most well-established processes for the production of SNG from syngas is the methanation technology; syngas is obtained from the gasification of coal and is further transformed in a series of adiabatic fixed bed reactors (Heidenreich et al., 2016). The methanation pathway could be considered an attractive process for obtaining bioSNG from waste-derived syngas (Materazzi et al., 2018).

Even in this application, fluidised bed reactors have demonstrated a higher performance compared to fixed beds in terms of CO conversion and CH_4 selectivity under the same reaction conditions (Liu et al., 2013). This is mostly due to the close-to-isothermal conditions and good catalyst mixing obtained in fluidised bed systems. It has been demonstrated that by using an $Ni-Mg/Al_2O_3$ catalyst, it is possible to achieve a CO conversion up to 95 % at atmospheric pressure, 480 °C and an $H_2/CO/N_2$ ratio in the syngas of 3/1/1 (Liu et al., 2015). From simulation studies, however, the optimum reactor configuration to carry out this operation was found to be an isothermal fluidised bed operating at 450–550 °C combining a tail-end fixed bed in which the CO conversion reached 99.8 % (Liu et al.,

2016). It also appears that the BFBs are more robust against C_2–C_3 contamination in the syngas, with a significantly lower carbon formation when compared to fixed beds (Kopyscinski et al., 2011).

The biological methanation of CO_2 in fluidised beds is also being investigated for the production of bioSNG from multiple sources. For example, the catalytic direct methanation of carbon dioxide can be carried out in a BFB, reaching an average yield and concentration of CH_4 equivalent to 96 % and 88 %, respectively. The results were obtained from experiments conducted in a biogas pilot plant in Zurich (Witte et al., 2019).

6.3 Liquid biofuels production

Similarly to bioSNG, liquid fuels such as Fischer-Tropsch diesel, biomethanol and bio-dimethyl ether (DME) are also gaining consideration as clean, drop-in replacements for fossil fuels.

Methanol can be obtained via the catalytic conversion of syngas from the fluidised bed gasification of both biomass (Liu et al., 2016) and waste (Iaquaniello et al., 2017). The plant in Edmonton run by Enerkem, Canada, is a commercially available example of methanol production from MSW (Arguin and Schubert, 2010). Methanol production is particularly relevant nowadays, not only because the methanol market is rapidly expanding, but also because it represents an ideal chemical platform for the generation of other fuels including gasoline, olefins and kerosene (Ilias and Bhan, 2013). For example, fluidised beds are widely applied in methanol-to-gasoline (MTG) processes, operating by means of a ZSM-type zeolite catalyst, as demonstrated by Wang and Yuan (2014). They have shown that the temperature range of 410–430 °C ensures a methanol conversion rate of 100 % and a gasoline yield up to 25 % at 410 °C (Wang and Yuan, 2014). Methanol-to-olefins (MTO) is another attractive process as these substances, mainly ethylene and propylene, are essential components in the chemical industry (Aghamohammadi and Haghighi, 2019). Producing light olefins (C_2–C_4) and clean fuels such as gasoline and middle distillates from syngas is also possible via the Fischer-Tropsch synthesis (FTS). Kang et al. (2011) demonstrated that with iron-based catalysts in BFB reactors at 300 °C, it is possible to reach the highest product selectivity when compared to fixed bed reactors. The authors concluded that the best catalyst candidate was K/FeO_x to obtain the highest yield of light olefins (i.e. up to 23 %) in the BFB reactor. In addition, recent studies demonstrate that by doping metal or metal oxides onto the ZSM-5 catalyst it is possible to produce aromatic species. This process is also known as methanol-to-aromatics (MTA). Laboratory trials have been carried out in a multi-stage fluidised bed system, allowing a stable yield of aro-

matics (at 62–66 %) to be reached (Chen et al., 2019).

7. Conclusions

In recent years, fluidised beds have been of special interest due to their potential as the central component in new thermochemical processes for utilising waste and biomass as sources of bioenergy and biorefinery products, notably in combustion, gasification and pyrolysis. This is because fluidised beds in all of their configurations offer a number of advantages over most other methods of heterogeneous solid fuels processing. These include steady temperatures, high rates of heat transfer and good solids mobility. Disadvantages include the attrition of solids, particle losses by entrainment, limited reactor efficiency because of the gas bypassing, and several issues in scale-up and design due to the complexity of the involved processes. This is even more evident when problematic fuels like municipal solid waste or waste biomass have to be processed due to their heterogeneous nature and high ash and moisture content.

This review is representative of the activity worldwide in the field of thermochemical processes that see fluidised beds as the core technology for the effective transformation of waste and biomass feedstocks. The application of fluidised beds for the catalytic synthesis of chemicals and biofuels is also briefly explored. Waste and biomass incineration is already widely applied commercially, while technologies for the conversion into biofuels or hydrogen are being gradually exploited, as shown in this paper. Although advanced technologies on lab and pilot scales have proven successful in many cases, they still struggle to be employed commercially due to competitive market factors that are beyond the scope of this review. It is expected that environmental policies and regulations will help the implementation of many sustainable technologies on a large scale in the coming years. Thus, the thermochemical processing of abundant and largely renewable sources like waste feedstock will play an essential role in shifting from fossil fuels to renewables quickly, economically and with low technological risk.

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Authors' Short Biographies
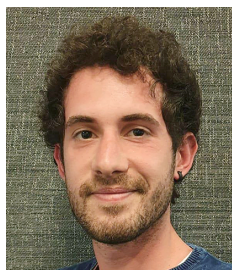
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Stefano is a new PhD student at the University College London (UCL), working on fluidised beds applied to the thermochemical treatment of biomass and waste. He graduated from the University of L'Aquila (Italy) in 2018, with his final-year project undertaken at UCL with the Erasmus+ programme. For his final MSc project, Stefano has developed advanced imaging techniques to better understand segregation phenomena during initial gasification and pyrolysis of waste feedstock in industrial reactors.

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Massimiliano Materazzi

Massimiliano is a research fellow of the Royal Academy of Engineering (RAEng) and lecturer of fluid particle systems in the Department of Chemical Engineering at the University College London (UCL). He has 10 years of combined industrial and academic experience in thermal processes and particle technologies spanning applications across the chemical, nuclear and renewable energy sectors. His research is oriented to several aspects of chemical recycling technologies, with particular attention given to the thermal treatment of problematic feedstock (e.g. household and industrial wastes), design of fluidised bed reactors for industrial applications, and catalytic processes for biofuel synthesis and chemical storage.