Chapter 4
Conversion of Biomass and Waste Fuels in Fluidized-Bed Reactors

Abstract Thermal conversion processes, namely combustion, gasification and pyrolysis are presented in this chapter. The conversion mechanisms that take place in fluidized-bed reactors are explained with emphasis on materials in-feeding, devolatilization and volatile conversion, char conversion and particle attrition and elutriation. A comparison between conventional and unconventional fuels is made, with particular focus on gasification of waste fuels for energy generation. The operating parameters in gasification processes are discussed, with reference to feeding (feeding methods, number of feeding points and solid fuel feed size), bed depth, bed temperature, fluidization velocity, equivalent ratio, and inerts content. To conclude, examples of current technologies which employ fluid-bed combustors, pyrolysers and gasifiers in operation in the UK and around the world are discussed. Advanced thermal processes such as fluid-bed plasma for waste gasification are also touched upon.

4.1 Introduction

The thermal conversion of new generation fuels in fluidized-bed reactors is discussed in this Chapter. Generally, such types of materials are classified as low grade fuels because their calorific value is relatively low compared to fossil fuels, or because they are in some way difficult to treat in conventional equipment. In some instances, for example, they can give rise to emission problems if treated conventionally, Doug Orr (2000). Such materials may occur naturally (e.g. biomass) or originate as waste materials (municipal solid waste, commercial and industrial waste, automotive shredder residues, etc.).

Given the rising concerns surrounding energy security and the increasing political emphasis on environmental sustainability, there are growing support schemes promoting the capabilities of waste-to-energy power generation in fluidized beds, Defra (2013). Waste-to-energy, or energy-from-waste, is the process of generating energy in the form of electricity and/or heat from thermal treatment of low grade fuels.

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Table 4.1 lists a number of the more common types of such fuels along with indications of their calorific value, ash content and water content. This list is intended merely to be illustrative and is in no way complete as the variety of waste fuels is almost endless.

The thermal treatment of low grade and waste fuels may be carried out for a variety of reasons; they include:

- the generation of heat, steam or power;
- the production of syngas (CO, H_2, CH_4) as precursors for chemical synthesis and advanced fuels generation.
- the treatment of a waste material to lessen its toxic properties;
- the utilisation of a low grade energy source to reduce fossil fuel demands or because there is no easier alternative;

changing of the physical form of a waste material (into pulverised ash for example) to make it more readily or economically disposable; it may even be possible to convert the waste material to a usable product (e.g. road paving material, construction material, etc.); low grade and waste fuels are often very variable in quality. This characteristic can make them difficult to use in conventional

Table 4.1 Classification of some types of low grade and waste fuels (BCURA 2005)

Fuel type	Calorific value (as received) MJ/kg	Ash (as received) % w/w	Moisture (as received) % w/w
Municipal solid waste	9–21	15–30	20–30
combustible components:			
– paper, cardboard	12–18	6	5
– wood	16–21	5–9	0.5
– textiles	15–20	0.5–3	2–10
– sawdust – plastics	18 17–40	1 10	3 2
– vegetables, garbage	18	16	70
– rubber, leather	18–26	10	1–10
Refuse derived fuel (RDF)	10	50	33
Industrial wastes			
– oil	19–30		
– paints	19–30		
– food processing	17–36		
– plastics	17–40		
– rubber, tyres	20–30		
Agricultural waste			
– wood chips	13	3.3	30
– paper	23	14	4.6
– sawdust	17	6	7

equipment but normally presents no problems for fluidized-bed conversion systems provided they can be fed to the reactor at a controllable rate and without interruptions in supply caused by variations in their physical nature. These fuels also vary enormously in their physical properties, calorific value and chemical composition as can be seen from Table 4.1. It is difficult, therefore, to give specific, quantitative design information for individual fuels. A generalised process scheme is then outlined and the factors to be considered at design stage are discussed. Finally, examples of advanced thermal technologies for specific application in the UK and in the world are given to illustrate the use of fluidized-bed reactors.

4.2 Thermal Conversion Approaches

Thermal conversion processes have been known and used for centuries. Despite this long history, development of advanced thermal conversion technologies for processing wastes has only become a focus of attention in recent years stimulated by the search for more efficient energy recovery and better ways of disposal.

Combustion, also known as mass burn incineration, is defined as the total thermal conversion of a substance with sufficient oxygen to oxidise the fuel completely. The general characteristic of combustion of a waste stream is that an excess air is required to ensure complete oxidation (maximum temperatures typically above 1000 °C); the fuel is completely oxidised to carbon dioxide and steam, leaving only a small amount of carbon in the ash (less than 3 % by weight of ash). Furthermore, all of the chemical energy in the fuel is converted into thermal energy, leaving no unconverted chemical energy in the flue gas and very little unconverted chemical energy in the ash.

Gasification is the partial oxidation of a substance with lower quantities (i.e. sub-stoichiometric) of oxygen compared to full combustion. Temperatures are typically above 750 °C, and products are gas (main combustible components being methane, hydrogen, and carbon monoxide) and a solid residue (consisting of non-combustible material and a small amount of carbon). The overall process does not convert all of the chemical energy in the fuel into thermal energy but instead leaves a big portion of the chemical energy in the syngas and, to a minor extent, in the solid residues (char). The typical net calorific value of the gas from gasification using oxygen is 10–15 MJ/Nm3.

Pyrolysis is the thermal degradation of a substance in the absence of added oxygen, at relatively low temperatures (typically from 300–600 °C). Products are oils and/or char (i.e. solid residue of non-combustible material and a significant amount of carbon), with synthetic gas as by-product. The latter consists in a mixture of carbon monoxide, hydrogen, methane and some longer chain hydrocarbons including tars. The char residue from pyrolysis processes could contain up to 40 % carbon representing a significant proportion of the energy from the input waste. Recovery of the energy from the char is therefore important for energy efficiency.

A wide variety of biomass and waste fuels can be handled successfully by fluidized-bed reactors and this process is considered to be more versatile than other more conventional forms of technologies, Scala (2013). Fuels in any physical form, and which may vary considerably in quality, can be converted successfully in a fluidized-bed reactor through the three approaches described above. The main characteristics of fluidized-bed reactors which make this high degree of versatility possible are as follows:

1. Rapid rates of mixing of the bed solids coupled with a relatively high thermal capacity of the bed solids. As a result considerable fluctuations in the fuel properties will not upset the process.
2. A relatively low reaction temperature which means that problems of volatilisation or of fusion of waste products are minimised. There is also a possibility that certain toxic heavy metal elements may be retained by the bed solids which can make their subsequent safe disposal easier, Williamson et al. (1994).
3. The ease of removal of the bed solids from a fluidized-bed reactor compared with conventional stoker or grate firing of solid fuels means that fuels with high inerts content are readily handled.
4. A fluidized-bed reactor can be operated, depending on the feed material, either autothermally or with auxiliary fuel injection. The auxiliary fuel may be natural gas or any other available material of reasonable calorific value (e.g. tyres and plastics).
5. The process can be operated to reduce emissions of tars to technically acceptable low values by the addition of solid sorbents.
6. The variety of feeding methods available makes it possible to feed fuel in any physical form and, if so desired, fuels in more than one physical form may be fed simultaneously.

4.3 Conversion Mechanisms in Fluidized-Bed Reactors

4.3.1 Fluidization and the Reacting Environment

In fluidized beds, the solid fuel and the bed material are intimately mixed and suspended on upward-blowing bubbles of fluidising gas. The upwards and sideways coalescing movement of bubbles provides intense agitation and mixing of the bed particles, which make fluid beds ideal for applications where high mass and heat transfer rates are required. In such systems (i.e. combustors or gasifiers), the particles are initially heated to above the ignition temperature of the fuel to be burned and then combustion/gasification takes place when the fuel is delivered into or onto the heated fluidized particles. The fuel burns (completely or partly) by virtue of the oxygen within the fluidising gas (air, oxygen, steam-oxygen or enriched-oxygen air), which is delivered by a fan (or blower) through the distributor plate and upwards through the bed particles. During steady-state gasification, temperature is controlled by the opposing effects of the heat input from the burning fuel in the bed, versus outgoing heat in the devolatilised gases and further heat ‘consumed’ by endothermic reactions in the gas-phase (e.g. steam reforming, water gas-steam carbon, etc.).

When considering gasification or combustion in fluidized beds it is important to remember that the oxidants leaving the distributor flows through the bed in two ways. According to the two-phase theory (Grace and Clift 1974), one portion—smaller—produce the dense phase, flows through the bed at the minimum fluidising velocity, and has good contact with the bed solids. The other portion, which in fluidized-bed gasifiers has a volume flow varying from 1.5 to 3 times that of the dense phase flow, forms the bubble phase. When they are first formed at the base of the bed the bubbles have good contacting with the dense phase but they rapidly coalesce as they rise up through the dense phase. The larger bubbles mix to only a limited extent with the dense phase and provide a gas flow which to some extent short circuits the bed and has a much shorter residence time than the dense phase.

Various refractory materials can be used to form the original ‘bed’ of particles, the most convenient being graded sand, around 1 mm in mean diameter, enabling fluidising velocities in the range 1–3 m/s. Alternatively, graded limestone or dolomite can be used if sulphur capture and/or tar reforming are required.

The produced gas leaving the freeboard is then forced to flow through a cyclone to separate part of the elutriated material (e.g. fly ash, unreacted char, bed particles, etc.), and cooled to (say) 200 °C before going through the gas cleaning.

Making a technical survey of fluidized-bed thermal conversion processes involves the analysis of several other phenomena, which include:

- Materials in-feeding
- Devolatilization and volatile conversion
- Char conversion
- Particle attrition and elutriation

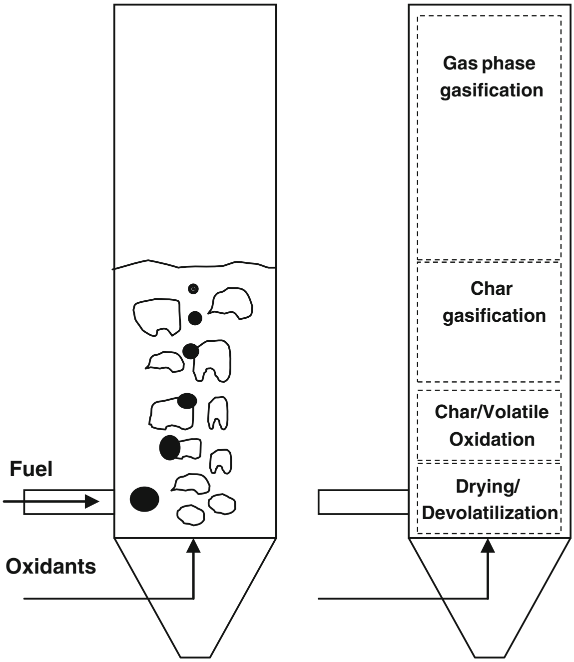
A more detailed description of the process in a fluid bed reactor follows in this Section.

4.3.2 Material In-Feeding

Fuel feeding in fluidized beds is one of the basic problems that has to be solved in order to achieve efficient conversion. Poor mixing of inert bed particles and fuel in horizontal direction, and short fuel particle residence time are two of the main drawbacks reported for bubbling fluidization at large scale, Gomez-Barea and Leckner (2010). In this sense, the way in which waste fuel is injected to the fluid bed reactor is a very critical point.

In-bed fuel feeding has been the first and most employed feeding system for fluidized-bed coal boilers in the past. Fuel is crushed to a size of ~5 mm, and dried to ensure moisture content not higher than 6–8 %, prior to transport and feeding, Oka (2004). Material is fed into the vicinity of the distributor plate from hoppers

Fig. 4.1 Generic bubbling fluidized-bed reactor schematization and process description (single in-bed feeding)



(Fig. 4.1), connected to screw augers via a rotary valve or a pneumatic conveying system, with slight nitrogen over-pressure to stop back feeding of producer gas and bed material through the in-feed. The basic advantage of this type of fuel feeding is the large residence time of fuel particles in the bed and higher conversion efficiency, Oka (2004). However, with operation on waste, the following issues are of concern:

- If the gasifier runs at greater than atmospheric pressure, there is potential for migration or leakage of hot gas into the fuel feed mechanism.
- Waste material is heterogeneous, both in composition and morphology. Bridging in hoppers and blocking of screw feeds are common issues with wastes. It is reported by Vreugdenhil (2010) that bridging in the feeding line was the main cause that resulted in abandoning pure waste feeding in circulated fluidized-bed gasifiers. Blockages may also be caused by large inerts in waste fuels. Drying and pelletisation are common techniques to provide a more homogeneous fuel form to aid feeding, and also by definition remove any large inerts above the pellet size. However this comes at high costs and energy penalties.
- The high levels of volatiles, especially plastics in municipal solid waste are likely to lead to rapid devolatilisation at the base of the gasifier, on contact with the hot bed material. This could exacerbate the issue of gas transport back up the in-feed and could lead to melting of the feed in the auger and exacerbate risk of blockages

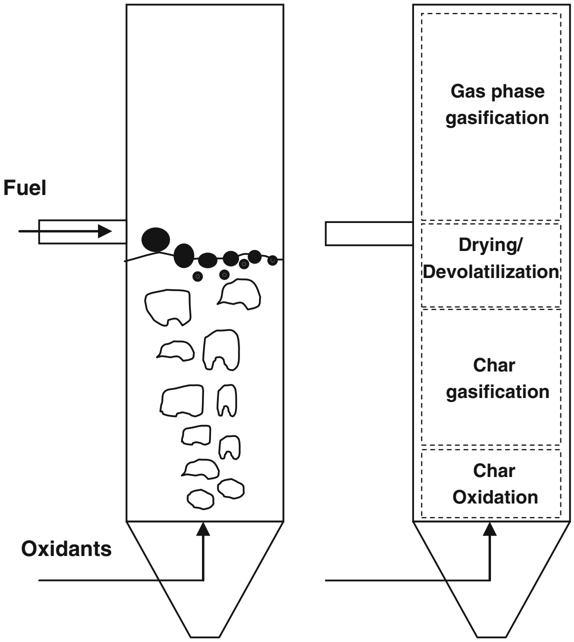


Fig. 4.2 Generic bubbling fluidized-bed reactor schematization and process description. Single over-bed feeding (*top*)

A different option is to inject the fuel directly over-bed by means of screw feeders (Fig. 4.2). These feeding devices were also developed for conventional fluid bed combustor boilers, and have been successfully applied in fluid bed gasification. A general advantage of over-bed feeding systems is the possibility of feeding moist and gross fuels "as received", with a particle range between 0–50 mm, although it is recommended that percentage of particles smaller than 0.5 mm should not be higher than 10 % for this type of systems, Oka (2004). The deficiencies of this type of feeding are its limits in terms of the need to specify a particular particle size range and the likelihood of elutriation of small particles and their subsequent conversion above the bed (rather than inside the bed). A further general deficiency of this type of system is the requirement for recycling/disposal of unreacted fuel particles, given the high elutriation losses that are likely to be experienced (see Sect. 4.3.5).

4.3.3 Devolatilization and Volatile Conversion

When the temperature exceeds 250 °C, the fuel particle organic matter starts to thermally degrade, with the detachment of the volatile matter from the solid fuel matrix (being 'char'), Basu and Kaushal (2009). This step is usually referred to as pyrolysis (or devolatilization), wherein water vapour, organic liquids and non-condensable gases, such as CO, H2, CO2, are separated from the solid carbon and ash content of the fuel. The vapour/liquid product comprises mostly of hydrocarbons and tar (i.e. dark, oily, viscous material, consisting mainly of heavy organic and mixed oxygenates). In absence of excess oxygen, the volatiles and char undergo a second conversion step and they modify their composition due to the occurrence of several reactions becoming a syngas (see Table 4.2).

Most of these reactions are endothermic and require a consistent amount of energy to proceed. This is usually supplied by the exothermic reactions within the same environment. Since the initial devolatilization is a rapid process, it has a negligible effect on the overall conversion time. Nevertheless, the location of devolatilization significantly affects the heat release profiles throughout the reactor.

On entering the hot fluidized bed most solid fuels initially decompose rapidly into a volatile portion which enters the gas phase and a solid portion or “char” which remains with the inert bed solids (Fig. 4.1). In view of the distribution of the air in a fluidized bed described above it can be seen that efficient in-bed conversion of gaseous products, and also of liquid and solid fuels producing a high proportion of volatiles, will only be obtained by feeding them at a relatively large number of points low down in the bed. Otherwise the volatiles will tend to react preferentially in the freeboard. This will occur, either if the volatiles enter the bubble phase, as the bubbles will by-pass the dense phase of the bed, or if the volatiles enter the dense phase, as the latter will tend to become oxygen deficient. In gasification, a modest proportion of freeboard combustion is acceptable although it is more efficient to burn the char within the bed rather than other volatiles in the freeboard, in which CO and H_2 are the most reactive. Excessive freeboard reaction, however, may result in an inability to maintain the desired bed temperatures if the heat release in the bed becomes less than the sum of the heat removed from it as sensible heat and as heat required for endothermic reactions, BCURA (2005).

Table 4.2 Typical reaction scheme, Materazzi et al. (2013)

Reaction name	Biomass gasification	Energy (kJ/mol)
Exothermic:		
Combustion	$(\mathrm{Char/Volatiles})\ C + O_2 \rightarrow CO_2$	−398.3
Partial oxidation	$(\mathrm{Char/Volatiles})\ C + 1/2\, O_2 \rightarrow CO$	−123.1
Water gas shift	$CO + H_2O \leftrightarrow H_2 + CO_2$	−40.9
CO methanation (I)	$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	−217.0
CO methanation (II)	$2CO + 2H_2 \leftrightarrow CH_4 + CO_2$	−257.0
Endothermic:		
Pyrolysis	$\mathrm{Biomass} \rightarrow \mathrm{Char} + \mathrm{Volatiles} + CH_4 + CO + H_2 + N_2$	+200−400
Methane steam reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	206.0
Water gas/steam carbon	$(\mathrm{Char/Volatiles})\ C + H_2O \rightarrow CO_2 + H_2$	118.4
Boudouard	$(\mathrm{Char/Volatiles})\ C + CO_2 \rightarrow 2CO$	159.9

4.3.4 "Char" Conversion and Fuel Reactivity

As the solid carbon-containing particles formed on initial decomposition of the fuel (or fed if the fuel is non-volatile), mix with the inert bed solids, heterogeneous reactions continue until the particle, is either burnt completely, or is discharged with the bed material for bed height control, or is removed from the bed by elutriation, BCURA (2005). This situation is likely to be the same for all fuels that have initially, or can form, carbonaceous 'char' particles irrespective of whether they are fossil or low grade or waste fuels in origin. The rate of reaction at the surface of a char particle will depend on the local air supply (determined by fluidizing conditions and the number of feed points for a fixed total feed), on the chemical activity of the carbon forming the char, and on the bed temperature, Basu and Kaushal (2009) and Scala (2013).

The chemical activity of the char varies according to the kind of fuel and how the char is formed. For example, it is well known that the chars derived from hard wood biomass are less reactive than those derived from soft wood biomass, Kersten et al. (2005).

4.3.5 Particle Attrition and Elutriation

This already complex picture is further complicated in a fluidized-bed reactor by the parallel ash release and comminution phenomena that can remarkably change the structure of mother fuel particles and then strongly affect its conversion process, Chirone et al. (1991) and Gomes-Barea et al. (2010).

If the fuel has only a very low, friable, ash content, the fuel ash is mainly degraded by the action of the fluid bed, such that it is substantially carried away i.e. elutriated (as 'fly ash'), within the emergent flue gases. Alternatively, if a high ash material is treated, especially one that leaves behind coarse particles of metals, glass or adventitious stone, some of the ash (named 'bottom ash') remains in the bed. If such ash is of similar size to the original bed particles, the ash will fluidise and eventually coexist with the original bed particles.

The process through which particle size decreases and ash is released includes the following four steps: primary and secondary fragmentation, attrition by abrasion and percolative fragmentation (Fig. 4.3). Primary fragmentation (Chirone et al. 1991) occurs immediately after the injection of the fuel particle into the bed, as a consequence of thermal stress caused by rapid heating and by volatile release. It generates coarse particles whose size and shape are influenced by fuel properties such as volatile content and swelling index. Secondary fragmentation and attrition by abrasion (Chirone et al. 1991) are determined by mechanical stress due to collisions between particles and with the furnace interior: the former generates coarser and non-elutriable fragments while the latter generates finer and elutriable

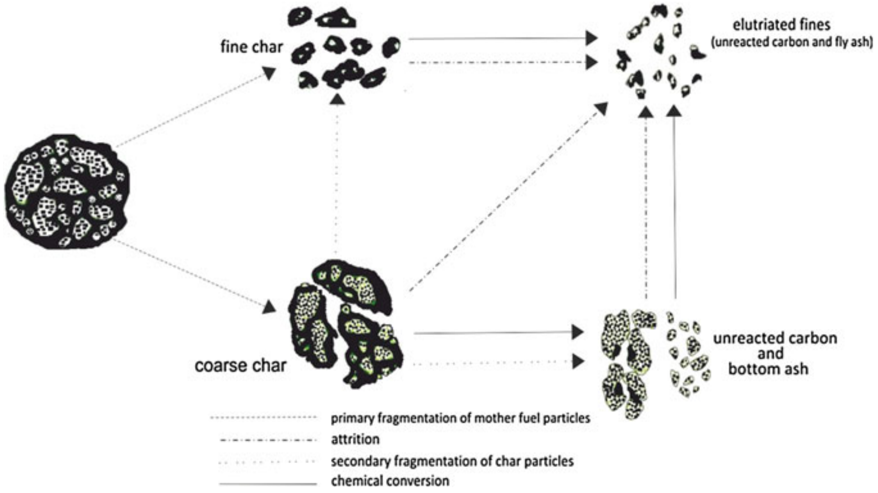


Fig. 4.3 Schematic of the series-parallel comminution phenomena of a solid fuel particle during a gasification process in a fluidized-bed reactor, Scala (2013)

fragments. Secondary fragmentation is favoured by swelling index, particle size and oxygen concentration increases. The oxidation conditions in the bed control attrition by abrasion, too. Experimental measurements reveal that, after an initial period of high attrition, the generation of fine particles reaches a stationary value proportional to the excess gas velocity above the minimum for fluidization and to the total carbon surface exposed in the bed, Ross and Davidson (1981).

The phenomenon that most affects carbon conversion efficiency is elutriation. This is the process in which fine particles are carried out of a fluidized bed due to the fluid flow rate passing through the bed. Fine particles that are subjected to elutriation can directly come from the fuel fed to the fluid bed gasifier or, alternatively, they can be produced during the gasification process and attrition.

4.3.6 Comparison Between Conventional and Waste Fuels

Gasification of waste fuels in fluidized beds includes a wide variety of non-fossil solid materials, ranging from mixed plastic to municipal, agricultural and industrial waste. Although there is a certain amount of operating experience in connection with this topic, (Saxena and Jotshi 1994 and Anthony 1995), a complete comprehension of the phenomena occurring during fluidized-bed treatment of these fuels, refuse-derived fuels in particular, is still lacking, probably due to the great difference in physical and chemical features from conventional ones. In fact, waste fuels are characterized by high moisture and volatile content, a porous and fragile structure, a low density and high intrinsic reactivity. The potential of a large quantity of moisture in fuel particles amplifies drying time and postpones devolatilization. On the contrary, low moisture and the high volatile contents lead to shorter devolatilization times and larger quantities of volatiles evolved: as a result, a larger contribution to the overall heat release is associated with drying process and homogeneous volatile reactions. Refuse-derived fuels devolatilization is completed at (or close to) the bed surface and a large fraction of the volatile matter is released directly in the freeboard: a direct consequence of bypassing the bed is that the post-conversion of volatiles in the splashing region leads to significant local overheating with respect to the bed, Scala (2013). Besides, fine carbon particles are significantly formed by attrition and fragmentation of coarse particles: this feature reflects the propensity of such fuels to give rise to either friable chars or even to a multitude of fragments of very small size. As a result, the conversion of fixed carbon occurs as much through the generation of fines, followed by their conversion over their residence time in the bed, as through direct conversion of coarse char particles. Because of high reactivity, the fine char particles are mostly burned in the bed, Anthony (1995). Whereas conventional fuels like coal undergo moderate primary fragmentation: after devolatilization about 99 % of the fixed carbon can be found in coarse char particles. Consequently, coal conversion occurs primarily in the bed, mostly via coarse char particle direct combustion.

The high quantity of fly ash and volatile material in wastes can also provide a decrease in thermal output, create high ash clinkering, and increase emission of tars and particulates, Materazzi et al. (2015). In fact, these reactors need to be operated at lower temperatures to prevent sintering of the ashes causing defluidization of the bed and, consequently, tend to produce a syngas containing high levels of condensable organics and gaseous hydrocarbon species which can be problematic in subsequent stages. Furthermore, the large quantities of gases and vapours leaving the solid matrix can entrain organic and inorganic material, even if the material itself is non-volatile, thus producing a large amount of residues downstream. As a result, the combination of high velocities in fluidized-bed reactors and high volatile matter in waste fuels indicates a potential for creating significant tar condensation and fly ash deposition problems during thermal treatment, with the severity varying significantly with the different nature of the feedstock, Miles at el. (1996).

4.4 Operating Parameters

4.4.1 Feeding Methods

The choice of the feeding method may often be a key factor in the design of a fluidized-bed gasifier to handle a low grade or waste fuel. It will often be desirable to carry out experimental tests to determine the optimum feeding method, BCURA (2005).

When choosing a feeding method the following general points should be borne in mind.

- Light and/or small sized particles which are readily elutriated are best fed near the base of the bed to give the maximum opportunity for reacting within the bed. It may be advantageous to feed such materials premixed with a suitable carrier.
- Solids with a high volatiles content (e.g. municipal solid waste, mixed plastics, etc.) are best fed near the base of the bed at a relatively large number of inlet points so that good initial mixing between air and fuel is achieved.
- Over-bed feeding methods will give more in-bed gasification if the fuel is deposited just above the bed surface rather than dropped from a height.
- Loosely adherent material like sludges may tend to flow erratically with lumps falling into the bed. Such lumps are often easily broken up by the particle movement in the bed and may not present a problem in maintaining a state of good fluidization.

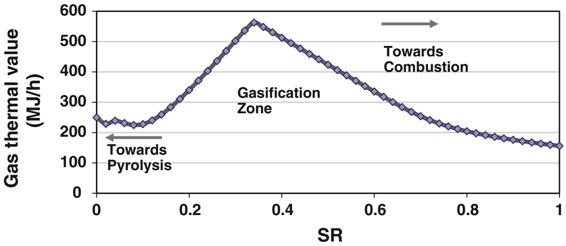
4.4.2 Equivalence Ratio

The oxygen used in a process determines the products and temperature of the reaction. The oxygen consumed is typically plotted as the equivalence ratio, i.e. the oxygen used relative to that required for complete combustion. A very low or zero oxygen use is indicative of pyrolysis, shown at the left of the figure. An equivalence ratio (SR) of about 0.25 is typical of the gasification region at the middle; and combustion is indicated by a SR = 1 (Fig. 4.4).

A further consequence of the division of the air into two portions, as described above, is that it is impossible to obtain complete combustion of any fuel in a fluidized bed using a stoichiometric supply of air. It is recommended that, in general, the equivalence ratio level should not be higher than 15 % for any fuel (i.e. SR = 1.15). For some biomass fuels, however, acceptable combustion can be obtained at an excess air level of 10 % (SR = 1.1), BCURA (2005).

Since some of the air in the bubble phase by-passes the bed, the bubble phase can be regarded as an additional air supply to the freeboard, and there is normally no need to make provision for any additional air supply direct to the freeboard as is sometimes done in incineration applications using other types of combustor.

Fig. 4.4 Influence of equivalence ratio (SR) on gas thermal value from gasification of refuse-derived fuels (30 kg\h of dry municipal solid waste), Materazzi et al. (2015)



4.4.3 Number of Feed Points

Mixing of the solids in a fluidized bed is a relatively rapid process particularly in a vertical direction and radially at the top and bottom of the bed. However, if the feed rate of a fuel containing a significant proportion of volatile combustible matter, to a particular point in the bed is too great, the dense phase gas may become locally sub-stoichiometric with a consequent fall in the rate of conversion. Analogously, if the proportion of combustible matter to a particular point is too low, full combustion takes place with a consequent fall in syngas yield.

4.4.4 Bed Temperature

The bed temperature should be a minimum of 750 °C to obtain acceptable rates of conversion of the char. The char conversion rate increases with increasing temperature and hence, the higher the bed temperature, the greater the conversion efficiency, Basu and Kaushal (2009). However there must never be any danger of sintering of the bed solids and there may be other restrictions which limit the usable bed temperature.

Temperature can also influence the amount of tar formed as well as the composition of tar. Kinoshita et al. observed that the total number of detectable tar species produced from sawdust gasification decreased with increasing temperature, Kinoshita et al. (1994). Lower temperatures favoured the formation of more aromatic tar species with diversified substituent groups, while higher temperatures favoured the formation of fewer aromatic tar species without substituent groups.

The consensus seems to be that temperatures in excess of 1000 °C are necessary to destroy the refractory unsubstituted aromatics. In order to avoid melting of the inorganic phase and total defluidization of the bed, such high temperatures are not achievable in a stand-alone fluidized bed, and a separate unit (called ‘thermal cracker’) is normally needed, Materazzi et al. (2014).

4.4.5 Solid Fuel Feed Size

The reaction of char particles is largely, though not exclusively, a surface phenomenon. Therefore, at a constant bed temperature a greater char concentration in the bed is needed for large particles than for small ones to maintain the same burning surface area in the bed. The carbon concentration in the bed solids depends therefore on the rate of combustion and on the fuel feed size. It also depends on the fluidising velocity since the latter determines the minimum size of particle that can remain in the bed without elutriation. The carbon concentration in the bed ranges from 0.1–0.5 % w/w for solid fuels with up to 10 % inerts fed pneumatically as granules, to 2.5 % w/w or more for fuels with a high (>50 %) inerts content and low reactivity, BCURA (2005).

4.4.6 *Effects of Inerts Content*

The inert matter is likely to affect the fluidization characteristics. This is due to (a) different morphology, (b) different chemistry, particularly dilution of an active bed material such as olivine (c) different melting points, which will be relatively uncontrolled. The consequences of this are potentially (a) higher tar levels in the existing gas, (b) agglomeration and fusing issues in the bed, (c) changes to the fluidization characteristics which could lead to heterogeneous heat distribution (d) a change in the through-bed pressure profile.

The issue of agglomeration is potentially the most serious of these, and was raised as a concern in the literature, Öhman et al. (2000). The solutions proposed in industry indicate a requirement (a) for more frequent replacement of the bed material and (b) tighter specification of the fuel. Both of which have significant operational cost implications.

A solid inerts content in the fuel can also affect the conversion process in two other ways. Firstly, the char activity can be reduced because the inert components hinder the quantity of oxygen to the carbon in the char particles. Secondly, the higher the inerts content, the higher the bed overflow or discharge to maintain a constant bed depth—unless the inert compounds are so finely divided to leave the bed by elutriation. Carbon losses with the bed overflow depend on both the overflow rate and the carbon concentration. The latter, in turn, depends mainly on the feed size, as discussed above. Carbon losses with the bed overflow may become significant for fuels with inert contents more than 50 %. The inert stream will also remove part of the heat of reaction. If the inert material is solid this component of the heat balance is usually a minor one unless the fuel is a high ash material. However if the inert material is water, the latent and sensible heat flows may be major components-of the heat balance. Additional loss of carbon and of sensible heat in the bed solids overflow will also be incurred when additives are used for tar reforming. These losses could become significant for high tarrous fuels.

4.4.7 *Bed Depth*

An increase in the bed depth will give an increased residence time both for the gas and the char particles. The resulting improvement in the reaction taking place within the bed may be balanced by a decreased proportion of freeboard conversion if the freeboard temperature is allowed to decrease. However in designs where the freeboard temperature is maintained constant, or separate reforming stages are employed (such as plasma converters), then an overall improvement in gasification efficiency can be obtained.

4.4.8 Fluidizing Velocity

When a reacting char particle is reduced to that size for which the fluidising velocity equals the terminal free fall velocity then that particle will be elutriated from the bed. The fluidising velocity, therefore is probably the most important parameter affecting the in-bed thermal conversion efficiency since it determines the size of particles that will be elutriated from the bed and also the residence time of the fine particles in both the bed and the freeboard. Low velocities (below 3 m/s) result in a bubbling fluidized bed, where only a small degree of expansion ensures that bed material and char stay inside the reactor. The effect of an increase in the fluidising velocity on particle elutriation can be marked since the size of particle elutriated increases rapidly with increasing velocity. High gas velocities (5–10 m/s) cause the bed to expand throughout the entire reactor volume which results in a significant entrainment of solid particles from the reactor. For this reason, a cyclone is usually positioned directly downstream of the reactor to capture and recycle the solids fraction. This configuration is typical of circulated fluid beds. The effect of increasing the fluidizing velocity on the overall conversion efficiency may not be marked at first since increased elutriation of carbon may cause increased freeboard reactions. Nevertheless, the combined effects of an increase in the fluidizing velocity in increasing the size of particles elutriated as well as decreasing their residence time (when the material is not recirculated) will result in a significant reduction in overall conversion efficiency at high values of fluidizing velocity.

4.5 Examples of Industrial Applications

4.5.1 Fluidized-bed Combustion

Although fluidized-bed technology has a limited track record in the UK for municipal solid waste treatment, there are over 150 plants in commercial operation in Europe and Japan. This is because fluidized beds have the ability to handle waste of widely varied properties and the many advantages in controlling emissions, McLanaghan (2002).

As opposed to its direct competitor moving-grate, fluidized-bed combustion processes require the pre-sorting and processing of municipal solid waste into refuse-derived fuels. Other advantages of fluidized beds include higher combustion efficiency that is comparable to pulverised fuel-fired combustors; reduction in boiler size; low corrosion and erosion with easier ash removal; and simple operation with fast response to load fluctuations.

Since the introduction of fluid bed combustors, there has been a series of mergers and acquisitions resulting in four major market players; Alstom, Foster Wheeler, Lurgi and Kvaerner Pulping, as shown in Table 4.3. Alstom and Foster Wheeler are the largest producers of circulated fluidized-bed technology (CFB), while Kvaerner is the market leader for bubbling fluidized-bed (BFB) technology. Bharat Heavy Electricals and Energy Product of Idaho are only active in their own regions in India and North America, respectively, Koornneef et al. (2007).

The commercial capacity of the fluidized-bed combustors are influenced mainly by the cross-sectional area of the vessel. Therefore, fluidized-bed designs need to be optimised with the emphasis on outstanding engineering innovations to achieve economical vessel arrangements and reach large commercial scales. An emerging technology in this field, is the Twin-internally Circulating Fluidized-bed Furnace developed by Ebara. The technology is licensed to Lurgi and trades in Europe under ROWITEC®, which is now a well-proven process and economically a competitive option compared to moving-grate combustion.

The Madrid energy from waste incineration facility in Spain is one of the highly successful operational plants employing the ROWITEC® process and proving its operational availability in excess of 90 %, Lischke and Lehmann (2001). The plant handles 20 tonnes of waste per day, which is approximately one third of the city's

Table 4.3 Overview of fluidized-bed combustion technologies

Manufacturer	Technology	Capacity (MWe)		No. of installations	Start-up
		Min	Max		
Alstom	BFB	17	142	7	1988–99
	CFB	2	520	51	1986–2005
Babcock and wilcox	CFB	3	76	22	1982–2002
Babcock borsig	BFB	0	35	5	1982–2000
	CFB	9	120	10	1989–99
Bharat heavy electricals	BFB	5	50	18	1987–98
EPI	BFB	10	45	9	1981–93
Foster wheeler	BFB	0	117	51	1976–2002
	CFB	0	460	161	1981–2006
Kvaerner pulping	BFB	6	117	56	1985–2005
	CFB	0	240	32	1984–2002
Lurgi	CFB	9	225	35	1982–2004

Adapted from Koornneef et al. (2007)

waste and generates 25MWe of electricity that can be fed into the public grid. It also consists of sorting lines for material recycling and a composting unit.

Other successful facilities employing the ROWITEC® process include plants in Gien and Mulhouse (France), Moscow (Russia), Vienna (Austria) and the Allington plant in the UK, Fujimura and Naruse (2001). The technology has a fairly simple mechanism with no moving parts inside the furnace. It has a slanted bed floor and the air flow rate is controlled to produce a revolving sand motion. It is this mixing effect that produces a combustion performance superior to that of conventional fluidized-bed furnaces.

4.5.2 Fluidized-Bed Gasification

Large scale fluidized-bed systems have become commercial due to the successful co-firing projects, such as the Kymijärvi Power Plant at Lahti in Finland. Furthermore, fluidized beds have the advantage of extremely good mixing and high heat transfer, resulting in very uniform bed conditions and efficient reactions. Circulated fluidized-bed gasifiers, in particular, are targeted for larger scale applications (Juniper 2007), as they can be used with different fuels, require relatively compact combustion chambers and allow for good operational control. There are several leading and state-of-the-art biomass and waste fluidized-bed gasification projects across the world.

Ebara has developed a ‘new’ generation gasification technology based on its internally circulating bubbling fluidized-bed incinerator and, in 2004, had 21 process lines in commercial operation in Japan and Germany. The technology, branded TwinRec, is a state-of-the-art twin internally circulating fluidized-bed gasifier. It is designed with ash vitrification technology for material recycling, energy recovery and detoxification of waste in an integrated and economical process. The gasifier is a revolving fluidized bed, which gasifies waste and produces heat that is used to raise the temperature in the next-stage slag combustion furnace. Due to the high temperatures inside the furnace, dioxins are decomposed and the ash is vitrified and recycled as stable glass granulates. Aomori is the largest gasification and slagging combustion system in Japan, with a capacity of 450 tonne per day and a power output of 17.8 MWe using a steam turbine, Selinger and Steiner (2004).

Enerkem’s Biosyn gasification process is based on a bubbling fluidized-bed gasifier that operates at 700–900 °C and up to 1.6 MPa. The process proved the technical feasibility of gasifying biomass from forest and agricultural residues, as well as refuse-derived fuels, rubber resides and sludge, Yassin (2008). The technology is available in the UK and Ireland under license by Novera Energy Europe. The Novera/Enerkem gasification technology is built cost-effectively at a smaller scale than combustion processes so it complies well with the proximity principal for waste disposal. The process has a low emission profile and is easily operable well inside the emission limits set under the Waste Incineration Directive. In late 2006, Novera Energy has signed a contract with Defra to build a gasification plant at the Ford plant in Dagenham in partnership with East London Waste Authority, Shanks and the Ford Motor Company. The plant will process 90,000–100,000 tpa of RDF supplied from the nearby Shanks MBT (mechanical biological treatment) plant at Frog Island. It will provide Ford with 8–10 MWe of electricity, which is equivalent to approximately £4 million per annum worth of electricity purchased from the national grid, while East London Waste Authority will benefit through the Landfill Allowance Trading Scheme, Yassin (2008).

Foster Wheeler has been supplying fluidized-bed gasifier systems for many years. The Kymijärvi Power Plant at Lahti in Finland is one of the most successful commercial demonstration plants coupling gasification with co-firing. The plant is a pulverised coal fired steam plant that generates up to 167 MWe of electricity and up to 240 MWth of district heat. It uses a circulated fluidized-bed gasifier to produce a low calorific product gas, which is combusted in the coal-fired boiler, thus replacing about 30 % of the coal. The gasifier uses biofuels, such as saw dust, wood residues and recycled fuels comprising of cardboard, paper and plastics, Spliethoff (2001). In addition, FW has contributed to the construction of the first complete Integrated Gasification Combined Cycle power plant at Värnamo in Sweden. The demonstration plant employed a pressurised air-blown circulated fluidized-bed gasifier operating at 950–1000 °C and 2 MPa, Stahl and Neergaard (1998). It fed about 6 MWe of electricity to the grid and 9 MWth of heat to the district heating network of the city of Värnamo.

FERCO has acquired the SilvaGas process from Battelle, who started developing this gasification process in 1977. The process uses forest residue, MSW, agricultural waste and energy crops and converts them into a syngas. The SilvaGas process consists of two interconnected atmospheric pressure circulated fluidized-bed reactors for steam gasification in one reactor, and a residual char oxidation with air in the second one, with solids exchange between the two reactors. The first commercial scale biomass gasification demonstration plant based on the SilvaGas process was built at the McNeil Power Station in Burlington, Vermont, USA. The syngas was used as a co-fired fuel in the existing McNeil power boilers and in a combined cycle with a gas turbine power generation system, Paisley et al. (1997).

The Gas Technology Institute, through its predecessor organisations (the Institute of Gas Technology and Gas Research Institute), has originally developed the air-blown Renugas technology for Integrated Gasification Combined Cycle gasification applications. The technology is based on a single stage pressurised bubbling fluidized-bed gasifier, with a deep bed of inert solids, which is also capable of producing a hydrogen-rich fuel. A 15 MWth pilot plant was commissioned in 1993 in Tampere (Finland) by Carbona, who licensed the Renugas technology from the Gas Technology Institute. The plant has operated for more than 2000 h on paper mill wastes, straw and coal mixtures, alfalfa stems and a variety of wood fuels, Arrieta et al. (1999). In 2004, Carbona has signed a contract to build a biomass combined heat and power gasification plant in Skive (Denmark). The plant will produce 5.5 MWe of electricity using gas engines and 11.5 MWth of district heat for the town of Skive, Babu (2005).

The Lurgi circulated fluidized-bed gasifiers operate at near atmospheric pressure and are well suited for capacities up to 30 t/h of feedstock. The gasification plants in Pöls (Austria) and Rüdersdorf (Germany) were designed and constructed for use in cement industry. The Bioelecttrica project in Italy uses an atmospheric circulated fluidized-bed gasifier integrated with a combined cycle of a 10.9 MWe gas turbine and a heat recovery steam generator of 5 MWe. The fuel used is a mixture of wood chips, as well as forest and agricultural residues. The project was aimed at the demonstration of the technical and economic feasibility of power generation from biomass using Integrated Gasification Combined Cycle. In 2000, Lurgi has contributed to the construction of the 85 MWth circulated fluidized-bed wood gasification process at the AMER9 power plant in the Netherlands. The syngas from the gasification process is co-fired in a pulverised coal combustor unit replacing 70,000 tpa of coal, Willeboer (1998).

The gasification process developed by TPS is based on an atmospheric circulated fluidized-bed gasifier operating at 850–900 °C and is coupled to a dolomite-containing tar-cracking vessel. A pilot-scale refuse-derived fuel gasification plant was commissioned in Grève-in-Chianti (Italy) in 1992. The plant processes 200 tonnes of waste refuse-derived fuel per day, which is fed into two air-blown circulated fluidized-bed gasifiers, each with a fuel capacity of 15 MWth. The syngas is used in a steam boiler to drive a 6.7 MWe steam turbine. In the UK, the gasification technology of TPS was installed in a wood-fuelled Integrated Gasification Combined Cycle plant at ARBRE, Eggborough in Yorkshire (shut down in 2002). The syngas from the process was compressed and combusted in a combined cycle gas turbine to produce 8 MWe of electricity. In Brazil, there are two projects based on the TPS technology, which aim to demonstrate the commercial viability of biomass fuelled Integrated Gasification Combined Cycle using gas turbines. The first is a 32 MWe plant that utilises wood as a feedstock, while the second plant uses sugar cane baggasse and cane trash, with the intention of integrating the biomass Integrated Gasification Combined Cycle system into a typical sugar mill, Yassin (2008).

The Austrian Institute of Chemical Engineering at the Technical University of Vienna (TUV) and AE Energietechnik have developed a novel fluidized-bed gasifier reactor producing a product gas with a high calorific value of up to 15 MJ/Nm^3. The gasification process is based on fast internal circulating fluidized bed and consists of a gasification zone fluidized with steam and a combustion zone fluidized with air. The circulating bed material acts as heat carrier from the combustion to the gasification zone, Vreugdenhil (2010). A demonstration combined heat and power plant located in Güssing, Austria, applies this technology and it produces 4.5 MWth for district heating and 2 MWe from an 8 MWth fuel input. The plant was commissioned in 2001 and uses wood chips and residues from industry as feedstock.

Table 4.4 Summary of main biomass and waste fluidized-bed gasification projects

Gasification type	Technology developers
Heat gasifiers (syngas combustion)	
Pöls, Austria	27 MWth CFB, Lurgi
Rüdersdorf, Germany	100 MWth CFB, Lurgi
Co-firing gasifiers	
Amer, Netherlands	85 MWth CFB, Lurgi
Burlington, USA	50 MWe CFB, Battelle
Lahti, Finland	40–70 MWth CFB, FW
Ruien, Belgium	50 MWth CFB, FW
Zeltweg, Austria	10 MWth ACFB, AEE
IGCC plants	
ARBRE, UK	8 MWe CFB, TPS
Grève-in-Chianti, Italy	6.7 MWe CFB, TPS
Pisa, Italy	12 MWe CFB, Lurgi
Värnamo, Sweden	18 MW PCFB, FW
CFB gasifiers with gas engine	
Güssing, Austria	8 MWth FICFB, AICE
Skive, Denmark	11.5 MWth PBFB, Carbona

PBFB = Pressurised bubbling fluid bed
AICE = Austrian Institute of Chemical Engineering, TUV

Finally, the main biomass and waste fluidized-bed gasification projects covered in this section are summarised according to their configuration in Table 4.4.

4.5.3 *Pyrolysis*

Pyrolysis is a less proven technology when compared to gasification and combustion and has a limited track record in the UK on the treatment of municipal solid waste. Whilst established pyrolysis technologies for the treatment of certain specific waste streams exist, it is only in recent years that pyrolysis has been commercially applied to the treatment of municipal solid waste. Nonetheless, the liquid bio-oil has a considerable advantage of being storable and transportable, as well as the potential to supply a number of valuable chemicals. In this respect, it offers a unique advantage and should be considered complementary to the other thermal conversion processes. Although the best reactor configuration is not yet established, fluidized-bed technology, as for gasification, is one of the most efficient and economic technologies of actualising fast pyrolysis as it offers high heating rate, rapid devolatilisation and convenient char collection and re-utilisation. Ensyn and Dynamotive are major developers of fluidized-bed pyrolysis technologies.

Ensyn has been producing commercial quantities of bio-oil from its Rapid Thermal Process (RTP™), which uses a circulated fluidized-bed reactor, since 1989. The RTP™ produces liquid bio-oil, gas and charcoal, which can be sold as fuel. Ensyn has developed natural chemical products from the liquid that have a much higher value. These include food flavourings and other products that can replace petroleum-based chemicals. In addition, the charcoal by-product is easily and economically upgraded to a higher value carbon product. The RTP™ is characterised by a very rapid heat addition and very short processing times of typically less than one second at moderate temperatures and atmospheric pressure. The 70 tonne per day RTP™ facility in Wisconsin produces a number of food, natural chemical and liquid bio-fuel products and operates with an availability exceeding 95 %. Ensyn has supplied a 650 kg/h unit to ENEL in Italy and a 350 kg/h unit to Fortum in Finland, Yassin (2008).

Dynamotive owns the rights for its BioTherm™ process, which incorporates a bubbling fluidized-bed pyrolyser, originally developed by Resources Transforms International. The process produces high quality bio-oil, char and non-condensable gases, which are recycled to supply 75 % of the energy required by the process. The bio-oil can be used directly in gas turbines or diesel engines for power generation. The company is also developing a range of derivative bio-oil products including blended fuels, slow release fertilisers and speciality chemicals, such as BioLime®, a reagent used to control SOx and NOx emissions in coal combustion systems. In 2005, Dynamotive has entered the commercialisation phase with the launch of its 2.5 MWe combined heat and power facility in West Lorne, Ontario (Canada). This is the first bio-oil combined heat and power facility and is capable of processing 100 tonnes per day of bio-fuel, mainly wood, and incorporating a 2.5 MWe gas engine, Yassin (2008).

4.5.4 Fluid Bed Plasma Treatment

The use of plasma has increasingly been applied with pure waste treatment for its ability to completely decompose the input waste material into a tar-free synthetic gas and an inert, environmentally stable, vitreous material known as slag. Advanced thermal treatments of low grade fuels that utilise plasma, are demonstrated to produce a clean syngas suitable for energy production as a by-product of the vitrification of hazardous waste streams such as organic pollutants or oily sludges. These plants produce a tar free syngas but a relatively high degree of input electrical energy is required, especially for large scale plants where massive quantities of waste need to be treated. A possible solution is seen in focussing the application of the plasma to what it does best—the vitrification of solid residues (ash) and the cracking of tars and long-chain (and aromatic) hydrocarbons. The process of primary conversion itself (either gasification or pyrolysis) could be achieved most efficiently and at very significant scale by employing a conventional fluid bed reactor upstream of the discrete plasma step. Overall, the energy balance of combining these process steps in this way is significantly better than by direct plasma application. The carbon conversion efficiency is very high, plasma parasitic load is kept low and heat is recovered directly from syngas cooling, Materazzi et al. (2013).

Advanced Plasma Power (UK) developed a two stage process (the Gasplasma process) which combines fluid bed gasification with plasma technology (Fig. 4.5), to produce a clean low inert containing synthesis gas, for use directly in power generation in gas engines/gas turbines or as a precursor for waste-to-gas and waste-to-liquid applications whilst also recovering significant quantities of heat.

The first stage is a bubbling fluidized-bed gasifier operated in temperature range between 650 and 800 °C, where the intense gas/solids contacting ensures the high heat transfer and reaction rates required to efficiently gasify the waste fuel. The second stage is a direct current plasma converter that 'polishes' the producer gas by organic contaminants and collects the inorganic fraction in a molten (and inert) slag. This slag is formed by the melting ash particles that continuously separate from the gas stream. Additional solids (oversize material) from the BFB bottom ash may be fed into the furnace to form more slag. Unlike some other gasification technologies, there is no need of intermediate fuel gas cleanup between the gasifier and the ash melting plasma converter. The plasma power is controlled to provide a uniform syngas temperature (~1200 °C) and destruction of the residual tars and chars contained within the crude syngas. Downstream of the plasma converter, the syngas can be directed straight to a solid oxide fuel cell stack for power generation, or cooled to around 200 °C in a steam boiler prior to cleaning treatment to remove any residual particulates and acid gas contaminants. The refined gas can be then used for power generation (gas engines or gas turbines), for conversion to a liquid fuel, or used as a chemical precursor. The Gasplasma process delivers energy conversion rates of 90 % in terms of syngas production; the net exportable power generation efficiency for a commercial scale plant is significantly in excess of 25 %. Based on 100,000 tonnes per annum input of a typical refused derived fuel, a Gasplasma facility generates in excess of 20 MW of electrical power, Taylor et al. (2013).

The main advantage of coupling fluidized-bed gasifier and plasma technologies is that the oxidant addition rate and power input in the two-stage process can be controlled independently while, unlike single stage fluidized-bed gasifiers, the

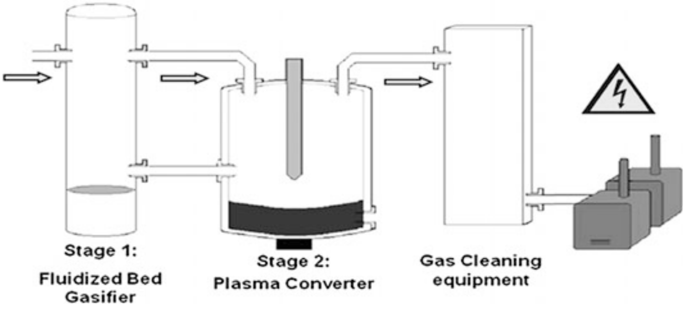


Fig. 4.5 Gasplasma schematic

gasification stability is not dependent on the gas evolved from the fuel itself. The energy input from plasma is readily controllable and (unlike oxidizing systems) is independent of the process chemistry, generating low off-gas volumes, reducing the size, complexity and the associated capital and operating cost of the downstream gas cleaning equipment and rendering the process flexible to changes in the refused derived fuel characteristics, typical of waste materials, Bosman et al. (2013).

Tar and ashes treatment from fluid bed reactors by plasma methods is one of the most concern topics for current scientific research and numerous treatment methods regularly emerge from the scientific community and are reported to be very effective in tar reduction and ash disposal but still need to be optimized to be economically viable and used industrially.

4.6 Conclusions

Thermal treatment processes including combustion, gasification and pyrolysis recover energy from waste in the form of heat and/or power. The heat can be used for district heating and the power can be easily distributed and sold via the national grid. Gasification and pyrolysis have the added advantage of producing a syngas that can be burned in conventional steam turbines or utilised in high efficiency gas engines and turbines. The syngas can also be further processed via gas synthesis to produce speciality chemicals and liquid fuels.

Fluidized-bed technologies offer alternative and reliable options to other Waste-to-Energy technologies because of their ability to handle waste of widely varied properties and the many advantages in controlling emissions. Although the technology has a limited track record in the UK for municipal solid waste treatment, there are over 200 plants in commercial operation in Europe and Japan.

The general conclusion drawn from the literature and experimental tests is that it is technically possible to convert a given material satisfactorily in a fluidized-bed reactor provided the following conditions are met:

- The material must be capable of being fed in such a way that it is quickly and evenly dispersed throughout the bed and remains there for a sufficient time for its conversion to be completed to an acceptable degree.
- The bed temperature must be such that there is no tendency for softening and melting (and consequent agglomeration) of any of the solid components in the fluidized bed.
- The fluidized bed must be maintained in a “well fluidized” state at all times. This condition implies that the fuel and its conversion products must be maintained in conditions such that no uncontrolled agglomeration of bed solids occurs.
- An appropriate provision for the removal of oversized bed material must be made for the treatment of fuels containing a significant proportion of oversize inert solid material (e.g. municipal solid waste).

Experimental testing will often be required to determine the optimum operating conditions for a particular fuel and application that comply with the above requirements. It should also be borne in mind that although it may be possible to treat certain materials using a stand-alone fluidized-bed reactor, it does not necessarily follow that it will be the best solution to do so. Often, complementary reforming steps in a multiple stage process can overcome most of the limitations of stand-alone reactors for use in waste thermal treatments.

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