NEXT GENERATION BIOMASS GASIFIER

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ABSTRACT: Gasification of solid fuels attracts increasing interest within the energy supply sector. Allothermal concepts typically use steam as gasification agent and require heat input from external sources. In the "classical" dual fluidized bed gasifier, heat is provided in direct contact with hot bed material particles externally heated in a combustion reactor. This type of gasification system is demonstrated in Güssing and Oberwart (Austria) and yields a high quality product gas. Thus, the gas is well suited for synthesis processes. However, a substantial improvement of fuel flexibility as well as overall efficiency of the process is necessary. In order to achieve these improvements the bubbling fluidized bed, which is used in the classical gasifier design, will be replaced by a countercurrent reactor with zones of solids accumulations in sections operated in the turbulent fluidized bed regime. Therefore, the gas-solids contact, which is important for tar reforming reactions, is increased significantly. Moreover, higher gasification rates and higher efficiencies can be expected due to the improved gas-solids interaction in the gasification section.

Keywords: gasification, reforming, dual fluidized bed, thermo-chemical conversion, tar, efficiency, product gas, steam

1 INTRODUCTION

Efficient utilization of biomass as a primary energy source reduces greenhouse gas emissions and reduces the need for long-distance transport of energy, thus increasing the security of energy supply. The main challenge is to develop new fields of application apart from simple heat generation. The dual fluidized bed steam gasification technology represents a key technology for both efficient combined heat and power production, as well as for coupled production of synthetic biofuels (2nd generation biofuels, polygeneration approach). The process has been developed at the Vienna University of Technology and is successfully demonstrated in Güssing and Oberwart at a scale of 8 resp. 10 MW_{th}. Various syngas upgrading and utilization technologies are currently investigated in national and international research projects. Some technologies, like production of synthetic natural gas are already in the large scale demonstration phase.

An increased interest from industry in technologies to substitute natural gas by using industrial waste fuels such as sewage sludge, municipal waste, saw dust, bark, waste wood, etc. [1], leads actually to a rethinking of the design of the gas generation section itself.

In the classical design of the dual fluidized bed biomass gasifier (like Güssing), the gasification reactor is designed as bubbling fluidized bed. The heat transfer to the fuel particles and the main tar destruction reactions take place in contact with the bed material particles inside the bubbling fluidized bed. Above there is a freeboard region where the solids concentration approaches zero. Such a separation between bubbling bed and freeboard leads to problems especially when inhomogeneous fuels are used. Organic fines are immediately elutriated into the freeboard where primary tars are emitted and not sufficiently converted due to lack of catalytically active solids in the freeboard. This may result in tar depositions down-stream of the gasifier and may critically affect the plant availability.

Recent research performed in the field of chemical looping combustion [2, 3] revealed that there is a significant improvement of gas-solids contact possible by increasing the fluidization velocity up to the turbulent or fast fluidization regime. These operating conditions also offer a promising approach in combination with dual fluidized bed gasification/reforming [4, 5]. In this case the bed material is distributed over the whole gasifier volume, partly elutriated at the top and recycled into the gasifier via a cyclone and loop seal. The change in fluidization conditions of the gasifier results in the following advantages: (1) The free-board disappears in favor of a zone with significant presence of solids. Organic fines pyrolyse in presence of catalytically active material and thus the tar destruction mechanisms work independently of fuel particle size. (2) The necessary reaction volume of the gasifier can be reduced and a scale up of the technology to larger capacities is favored. (3) The separation systems at the exit of both reactors lead to a defined backflow of coarse particles and also catalytically relevant fines into the gasifier system. It further prevents the product gas line from facing too high solid fractions.

The aim of the presented work is to investigate this promising approach at relevant operating conditions to provide the basis for the industrial demonstration.

2 DUAL FLUIDIZED BED GASIFICATION

2.1 State of the art

Many gasification technologies have been developed whereas the reactor types can be split up into four groups: fixed bed, fluidized bed, moving bed gasifiers and reactors of special design [6]. Dual fluidized bed gasifiers are used to produce a high quality product gas. The gasification section is generally heated with hot particles from the second fluidized bed, which is heated by burning the remaining char with air. Gasification can be realized as bubbling and combustion as circulating fluidized bed (CFB) [e.g. 7], the other way round [8], or even as combination of two CFB reactors [e.g. 9, 10]. However, other configurations such as the heat pipe reformer exist [11]. A review about classical concepts is given by Corella and co-workers [12] as well as by Göransson and co-workers [13]. In the following a short overview over promising designs, either in pilot or demonstration scale, is given.

Kagayama and Kunii tested DFB gasification for RDF (refused-derived waste) already in the 1970´s with a combination of two bubbling fluidized beds [14]. Another technical option with two circulating fluidized beds has been proposed by Paisley and co-workers in the 1980´s [9].

The so called Herhof-IPV process is under investigation at the University of Siegen, Germany [15] using a 150 kW_{th} pilot plant. The process is consisting of parallel operation of a fixed bed gasifier and a bubbling fluidized bed reactor as combustor. Biomass is fed into the fixed, dried, pyrolised, and gasified. Municipal waste is used as fuel and silica sand as bed material. Steam is used in the upper part of the fixed bed as well as in the loop seals. A high quality product gas with a lower heating value of about 13.3 MJ/Nm³ and nitrogen concentration less than 7 vol.-% is obtained.

The MILENA gasification process uses as well a bubbling fluidized bed as combustor whereas the gasification is carried out in a fast fluidized riser [8, 16]. The system is optimized for the production of substitute natural gas (SNG) out of biomass [17]. Tests with a 30 kW_{th} lab-scale facility revealed MILENA to be a stationary process producing a product gas, which contains very high amounts of hydrocarbons on energy basis. Cold gas efficiencies of 80 % are expected to be possible for large-scale systems.

At the Dalian University of Technology, China, the so called ECCMB (external circulating concurrent moving bed) system is under investigation in a 1 kg_{fuel}/h research facility [18]. This process combines a transporting fluidized bed acting as combustion zone and a gas-solids concurrent downflow-moving bed as gasification zone. Olivine is used beside its function as heat carrier also as catalyst to reform the tars. The combustion reactor is fluidized with air, whereas steam is used for the gasification part. The fuel particles are introduced to the system into the gasification section. Ungasified charcoal is transported to the combustion zone and combusted to heat up the bed material. The product gas from biomass gasification consists mainly of hydrogen (25 … 40 vol.-%), CO (50 … 30 vol.-%), CO_2 (10 … 15 vol.-%) and CH_4 (10 vol.-%), depending on the gasification temperature (650 … 800 °C) and the steam to biomass ratio (0.2 … 1.2).

At Ishikawajima-Harima Heavy Industries Co, Japan a DFB system, combining concentrically a bubbling fluidized bed gasification zone and a pneumatic transport riser as combustion zone, is developed to gasify residues from the food industry [19]. The gasification zone is fluidized by steam and the combustion zone by air. The fuels have originally more than 65 wt.-% moisture. In the first step the fuel is dried down to 10 wt.-% of moisture and in parallel fat is reformed to increase the ability for thermo-chemical conversion. The resulting product gas composition is comparable to the above described systems. As advantage of this system it should be mentioned that due to the compact design heat losses can be minimized.

A special concept of a dual fluidized bed gasifier is represented by the so called “Heatpipe Reformer” developed at the Technical University of Munich. This technology uses closed pipes filled with a working fluid such as sodium or potassium to deliver the heat from the bubbling fluidized bed combustion section to the bubbling fluidized bed gasification section by evaporation and condensation of the working fluid [11, 20, 21]. Thus, this concept can be classified as allothermal gasifier based on solid biomass. A high-calorific gas, free of nitrogen, is produced to be used for combined heat and power production as well as for synthesis processes.

The so called Chalmers gasifier represents a promising design similar to the dual fluidized bed gasification as described in section 2.2. Gasification is done in a bubbling fluidized bed and char combustion in the circulating fluidized bed [22]. This design is from the viewpoint of particle circulation, fuel conversion as well as tar levels an attractive design amongst the group of gasifiers. A 2-4 MW_{th} indirect gasification section is integrated into the loop of the existing 8-12 MW_{th} circulating fluidized bed (CFB) boiler at Chalmers University. After the cyclone of the boiler the particle stream is divided. A defined amount of hot bed material entrained from the boiler is so transferred to the gasifier providing the heat for the production of a nearly nitrogen free product gas. Non-gasified char is returned together with the bed material into the boiler and converted. Biomass can be fed into both sections; the boiler and the gasifier. The gasification is separated from the boiler via two loop seals and a particle distributer, directing particles either back to the boiler or into the gasification section. For that reason the CFB boiler can be operated even after the retrofit independently, just like before, or in combined combustion/gasification mode. This possibility keeps the risk for a retrofit low. As, furthermore, the investment costs for the integration are considerably lower than standalone gasification units of that size, the retrofit is an easy way to extend the potential and product spectrum of a CFB boiler towards bi- and tri generation (heat, power, fuel) and enter new markets.

2.2 Dual fluidized bed steam gasification at the Vienna University of Technology

Biomass steam gasification allows the conversion of solid feedstock (biomass, residues, coal, waste materials, etc.) to a medium calorific gas (12 – 14 MJ/Nm³) consisting mainly of H_2, CO, CO_2, CH_4 and H_2O (see Table I). At the Vienna University of Technology the dual fluidized bed steam gasification technology has been developed to provide the heat for the gasification reactor by circulating bed material. This system is a further development of the so called “Fast Internally Circulating Fluidized Bed” (FICFB) technology [23, 24, 25].

The principle of the dual fluidized bed steam gasification process is displayed in Figure 1 whereas Figure 2 shows how this concept is implemented technically. The feedstock is transported by screw conveyors directly into the bubbling fluidized bed gasification reactor. Several processes occur in parallel such as drying, devolatilization, pyrolysis, and partially heterogeneous char gasification whereas the bed temperatures are adjusted in the range of 850 – 900 °C. Residual biomass char leaves the gasifier together with the bed material through an inclined, steam fluidized chute towards the combustion reactor. The combustion reactor (so called riser) is operated in the fast fluidization regime with air as fluidization agent. Thus, the char is combusted to heat up the bed material. The hot bed material particles are separated from the flue gas in a cyclone separator and the hot particles flow back to the gasifier via a loop seal. The loop seal and the chute are fluidized with steam to avoid gas leakage between gasification and combustion zone and to allow high solid throughput. The system is inherently auto-stabilizing since a decrease of the gasification temperature leads to higher amounts of residual char which results in more fuel for the combustion reactor. The temperature difference between the combustion and the gasification reactor is determined by the energy needed for gasification as well as the bed material circulation rate. In practical operation, the gasification temperature can be influenced by an auxiliary fuel input (e.g. recycled product gas, saw dust, etc.) into the combustion reactor. The pressure in both, gasification and combustion, reactors is close to atmospheric conditions. The process yields two separate gas streams, a high quality product gas and a conventional flue gas, at temperatures higher than 800 °C. The product gas is generally characterized by a relatively low content of condensable higher hydrocarbons (4 – 8 g/m³ of so called tars, heavier than toluene), low N_2 (< 1 vol.-%db), and a high hydrogen content of 36 – 42 vol.-%db (a detailed gas composition is given in Table I). For practical use, olivine - a natural mineral, has proven to be a suitable bed material with enough resistance to attrition and moderate tar cracking activity.

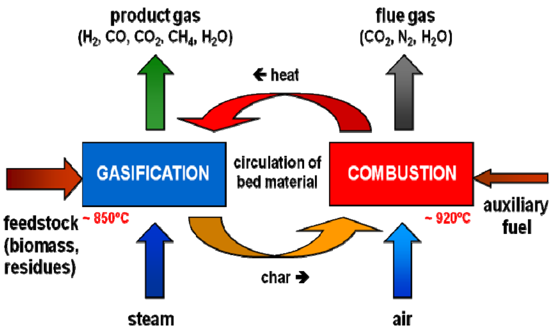

Figure 1: Principle of dual fluidized bed steam gasification for solid feedstock (conventional process)

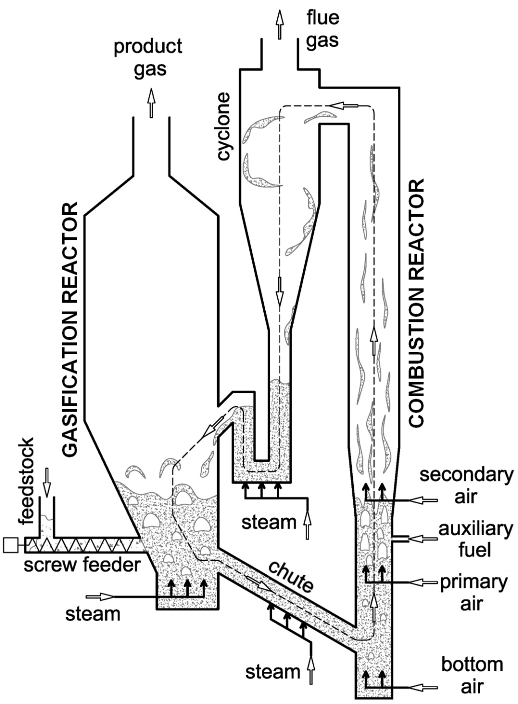

Figure 2: Classical dual fluidized bed steam gasifier

2.3 Dual fluidized bed steam gasification of solid biomass coupled with CO_2 capture

Recently a lot of research has been done to either remove carbon dioxide from flue gas streams of boilers [26, 27, 28] or to produce hydrogen rich gases [29, 30]. The process for in-situ removal of carbon dioxide by calcium oxide in gasification and reforming applications is well known for a long time [31, 32, 33].

A further development of the previously described dual fluidized bed steam gasification of biomass is the implementation of the sorption enhanced reforming process (SERP) which uses in-situ carbon dioxide (CO_2) capture by the bed material [34, 35]. Therefore the gasification temperature has to be reduced to temperatures below 700 °C. The principle of this process is shown in Figure 3, whereas in Table I typical ranges of gas composition in comparison to the conventional process is given. Apart from its functions as heat carrier and as catalyst the bed material transports selectively carbon dioxide from the gasification to the combustion section. This is done by repeated cycles of carbonation as well as calcination of the material according the following equation:

$$CaO + CO_2 \leftrightarrow CaCO_3 \qquad \text{Eq. 1}$$

Equation 2 displays the water-gas shift reaction which allows also removal of carbon monoxide from the product gas:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \text{Eq. 2}$$

This process offers the following advantages to the conventional operation mode of the gasifier: (1) internal reforming of tars (primary as well as secondary), whereas the formation of higher tars is inhibited (2) integration of exothermic carbonation as well as water-gas shift reaction into the gasification (3) the low operation temperature as well as the catalytically active CaO allows gasification of problematic feedstock such as biomass with high mineral and high moisture content, e.g. straw, sewage sludge. However, there are limitations (see section 3 Process Limitations) of the process in the actual design such as residence time and gas-solids contact since the carbonation needs high residence time with sufficient contact of the product gas and the bed material.

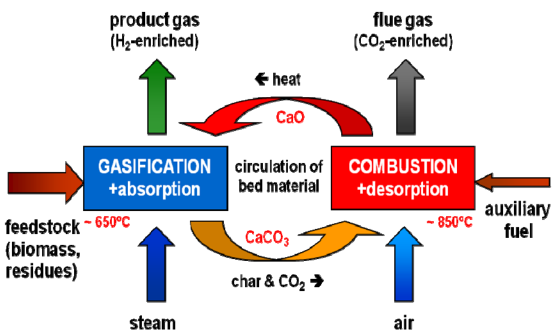

Figure 3: Principle of dual fluidized bed steam gasification with selective transport of CO_2 (SERP)

Table I: Typical product gas composition of the dual fluidized bed steam gasification process without and with selective CO_2 transport

component	unit	conv. process	SER process
H_2	vol.-$\%_{db}$	36 … 42	55 … 70
CO	vol.-$\%_{db}$	19 … 24	5 … 11
CO_2	vol.-$\%_{db}$	20 … 25	7 … 20
CH_4	vol.-$\%_{db}$	9 … 12	8 … 13
C_2H_4	vol.-$\%_{db}$	2.0 … 2.6	1.4 … 1.8
C_2H_6	vol.-$\%_{db}$	1.3 … 1.8	0.3 … 0.6
C_3-fract.	vol.-$\%_{db}$	0.3 … 0.6	0.3 … 1.0
tar	g/Nm$^3_{db}$	4 … 8	0.3 … 0.9
dust	g/Nm$^3_{db}$	10 … 20	20 … 50
H_2O	vol.-%	30 … 45	50 … 60
feedstock		wood pellets	wood pellets
bed material		olivine	calcite

3 PROCESS LIMITATIONS

A significant progress with regard to design development as well as to demonstration of dual fluidized bed gasifiers has been achieved within the last decade. Production of a high-quality syngas with manageable amounts of impurities from biomass is feasible. However, most of the designs work well for certain fuels whereas fuel flexibility, conversion efficiency and reliability are getting more and more important. The classical design of the DFB gasifier as proposed by the Vienna University of Technology is commercially demonstrated at several locations with wood chips from forestry as fuel. To meet future demands of this promising technology firstly an assessment of the limitations of the process has been accomplished. In the following the main limitations (classical design) are listed whereas it has to be mentioned that for a specific application not all limitations play a major role:

- Feedstock: flexibility and composition with regard to particle size, fines, ash content, moisture, volatiles content, heating value, liquid vs. solids
- Gas-solids contact with regard to the freeboard of the bubbling fluidized bed
- Residence time of fuel and products from drying, devolatilization, pyrolysis, and gasification in the fluidized bed
- Tar content as well as tar composition
- Entrainment of fine char particles
- Entrainment of catalytically active particles being important for carbonate looping ($CaO/CaCO_3$)
- Feedstock feeding with regard to residence time in the bed
- Overall efficiency with regard to steam-to-fuel resp. steam-to-carbon ratio
- Externally auxiliary fuel input in the combustion section needed
- Fuel power of the plant is limited by the bubbling fluidized bed

The evaluation of the above listed limitations respectively led to a suggested design of a novel dual circulating fluidized bed, whereas the gasification section is designed as countercurrent column with zones of bed material accumulations. This proposed reactor system, called G-volution gasifier, is described in the following chapter.

4 G-VOLUTION GASIFIER

The novel dual circulating fluidized bed (DCFB) concept with countercurrent effect in the gasification section and with multistage (additional) solids separation systems, for coarse and fine particles on each side, is displayed in Figure 4. The outstanding improvement of the G-volution design is the special construction of the gasification section with the fluid dynamics in this reactor. Thus, the gas-solids interaction is significantly improved. Gas as well as solids residence time is increased with regard to contact of bed material and the gaseous phase. Fluid dynamics in the reactor can be expected to resemble a multi-stage cascade of stirred vessels. The gasification reactor can also be described as a plug flow reactor for gas and a column of stirred vessels for solids, with the special characteristic that the gaseous phase and solids move in countercurrent directions. This includes that fresh, regenerated and hot bed material from the combustion reactor (CR) is present in the upper part of the gasification reactor (GR) before the product gas is leaving the gasifier. Thus maximize chemical and physical driving forces, ensure high conversion rates and low tar contents in the product gas. With increasing hold up of bed material the pressure drop is increasing in the gasification reactor. The pressure difference between the lower parts of the combustion and gasification reactor can be used to replace the externally auxiliary fuel input. Therefore a bypass directs hot product gas in a defined quantity from the gasification to the combustion reactor (see Figure 4).

Detailed results about the conversion of methane, hydrocarbons and tars, as well as cold flow modeling of the key modifications of the G-volution concept have been presented by Schmid et al. [4, 5] and Guìo-Pèrez et al. [36]. Based on those findings the following main advantages of the new gasification system can be expected:

- Smaller particle sizes of bed material reduces the necessary gas velocity and in the following attrition and abrasion effects
- Increases of the residence times for fuel particles as well as gases with regard to gas-solids interaction
- Feedstock can be fed at several positions depending on the fuel parameters (e.g. gaseous/liquid/solid, amount of volatiles)
- Global circulation rate predominantly controlled with fluidization rate of the combustion reactor
- Fast fluidized combustion reactor combined with a moderately fluidized gasification reactor with zones
- Turbulent fluidization in each stage (excellent gas-solids contact)
- Solids residence time distribution resembles a cascade of stirred vessels (dispersed downward movement of solids)
- Increased bed material hold up (and residence time) in the gasification reactor
- The countercurrent effect of solids and gas in the

gasification reactor maximizes chemical and physical driving forces over height

- Simple geometrical changes (good applicability to refractory-lined units)
- Entrained fines (like fine char and $CaCO_3$) out of the gasification reactor are fed back to the reactor system through a solids separator system
- A combination of hard coarse particles and softer fines is possible
- Classifying effect and countercurrent movement of coarse particles (downward) and fines (upward) in the gasification reactor
- Internal utilization of hot product gas to control process parameters (no need of external auxiliary fuel input to combustion reactor)

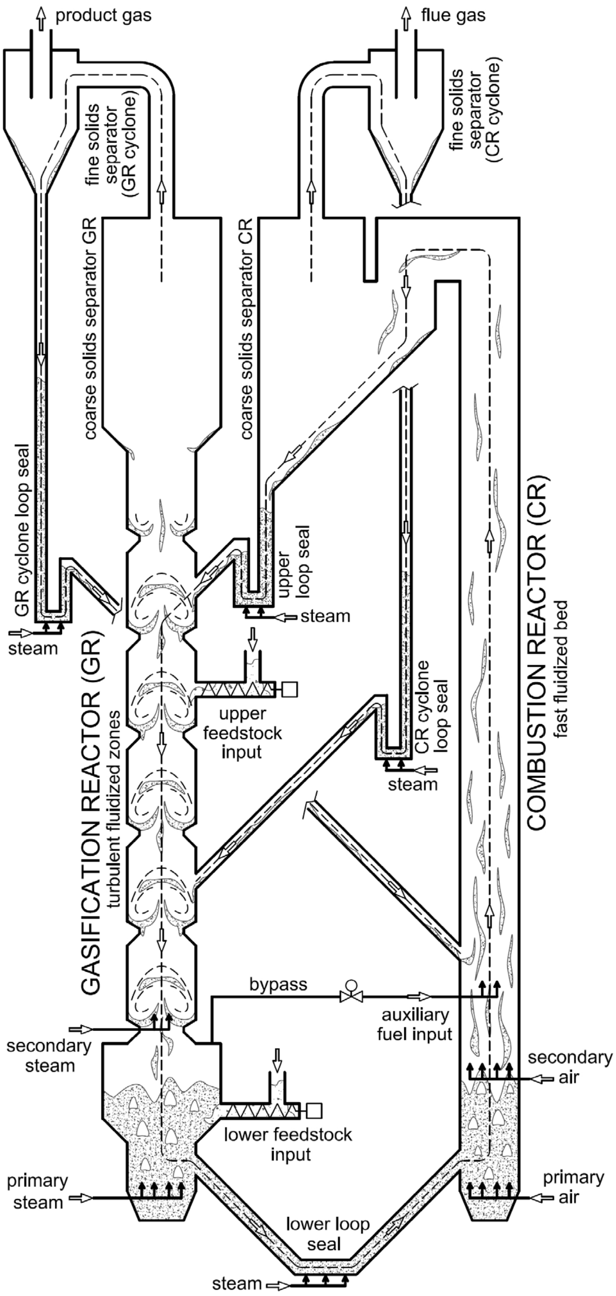

Figure 4: G-volution gasification system, next generation biomass gasifier

5 SUMMARY

A novel fluidized system with two reactor units interconnected with circulating solids is presented. The design is based on a dual fluidized bed gasifier concept. The global solids loop starts in the combustion reactor (CR) where solids are entrained. Coarse and fine bed material are separated from the flue gas stream and sent to the gasification reactor (GR) via steam fluidized loop seals (upper loop seal, CR cyclone loop seal). From the gasification reactor, the solids mainly flow back into the combustion reactor via a second loop seal connecting the bottom regions of the two reactors (lower loop seal). Fine solids entrained and separated from the gasification reactor product gas stream are also directed back into the system.

An extensive gas-solids contact is crucial to produce a high quality syngas out of various feedstocks, varying in composition, size distribution, ash content, and physical condition (gaseous, liquid, solid). Cold flow modeling as well as pilot scale experiments gained improved performance with increasing fluidization velocity, especially if comparing bubbling with turbulent fluidization regimes. Further improvement in gas-solids contact can be achieved by modification of the geometry of the secondary fluidized bed. The reactor is divided into a sequence of sections by constrictions whereas solids density is high above these constrictions. It is possible to feed the solids coming from the combustion reactor close to top of the moderately fluidized gasification reactor. Since the solids leave this reactor at the bottom, this allows an overall countercurrent flow regime of gas and solids. The fluid dynamics of the bed material in the gasification reactor is equivalent to a column of stirred vessels. Furthermore solid feedstock with high content of volatile compounds (like wood chips) or fines (like sawdust) can be fed close to the bottom of the fuel reactor. Coarse feedstock with low content of volatile compounds can be fed at higher regions. Optimal residence time distributions are possible depending on the location of feedstock input.

Summarizing, dual fluidized bed systems are increasingly used for energy conversion technologies such as steam gasification, sorption enhanced reforming (carbonate looping) and chemical looping processes (combustion respectively reforming). For all these processes intensive gas-solids contact is the key parameter. The proposed process of dual circulating fluidized bed design, in combination with countercurrent flow in the fuel respectively gasification reactor and zones of bed material accumulation, will result in higher conversion rates and overall efficiency. Moreover, improved gas quality with a reduced amount of tars can be expected.

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8 LOGO SPACE