A new dual fluidized bed gasifier design for improved in situ conversion of hydrocarbons

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Abstract: A new fluidized bed gasifier with increased gas–solid interaction combining two circulating fluidized bed reactors is proposed. The aim of the design is to generate a nitrogen (N_2) free product gas with low tars and fines content. Therefore the system is divided into an air/combustion and a fuel/gasification reactor. Two gas streams are separately gained. The two reactors are interconnected via loop seals to assure the global circulation of bed material. The global circulation rate is driven by the gas velocity in the air/combustion reactor. Furthermore the fuel/gasification reactor itself is a circulating fluidized bed but with the special characteristic of almost countercurrent flow conditions for gas phase and solids. By simple geometrical modifications it is possible to achieve well mixed flow conditions in the fuel/gasification reactor along the full height. The gas velocity and the geometrical properties in the fuel/gasification reactor are chosen in such a way that solids' entrainment of coarse particles is low at the top. Due to the dispersed downward movement of the solids, no volatiles are produced in the upper part of the fuel reactor and the problems of insufficient gas phase conversion and high tar content are avoided. Cold flow model results show the fluid dynamic feasibility of the novel dual circulating fluidized bed concept.

Keywords: fluidization, circulating fluidized beds, dual fluidized bed systems, countercurrent gas–solid interaction, gasification, sorption enhanced reforming, DUAL FLUID technology

1. Introduction:

An increased interest from industry in technologies to substitute natural gas by using industrial waste fuels, such as sawdust, bark, shrub cuttings, reeds, waste wood and other alternative feedstock from biomass has led to research activities focused on gasification technology [1]. The "classical" steam blown dual fluidized bed (DFB) gasification technology – nowadays named DUAL FLUID – was developed at Vienna University of Technology in the 1990's [2, 3]. In the "classical" design, the fuel reactor, also called gasification reactor, is a bubbling fluidized bed as shown in Figure 1. Heat transfer to the fuel particles and the main tar destruction reactions take place in contact with the slightly catalytically active bed material (olivine) inside the bubbling fluidized bed (BFB). Above there is a freeboard region, where the solids' concentration approaches zero. This commercially available design works well with uniformly sized woodchips and comparatively large bed material particle sizes (400 to 600µm) [4]. Two industrial plants with fuel inputs of 8.5MW$_{th}$ are in operation in Austria (Güssing, Oberwart).

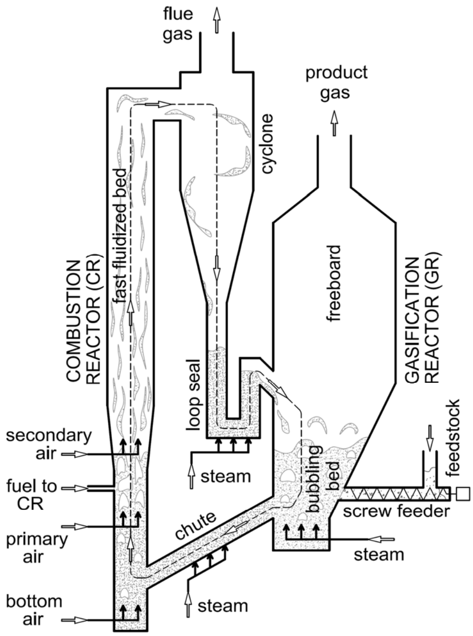

Fig.1: Classical dual fluidized bed gasifier design

In the case of industrial utilization, wood chips are a comparatively expensive fuel. To be able to use alternative fuels at a lower price, the focus of research and development lies in the gasification reactor system itself. The separation between the bubbling bed and freeboard in the shown classical dual fluidized bed gasification system is responsible for problems if inhomogeneous fuels, such as sawdust, dried sewage sludge, or waste wood, are used. Organic fines are immediately elutriated into the freeboard. Due to the lack of catalytically active solids in the freeboard, fine char and tars will not sufficiently convert. This may critically affect the plant availability and leads to problems in the downstream plant equipment.

2. Theoretical background:

Circulating fluidized beds are able to operate in higher velocity areas like turbulent or fast fluidization. With a circulating fluidized bed (CFB) design, smaller reactor dimensions, higher flow rates and a significant improvement of gas–solids contact are possible. The behavior of a continuous fluidization, later called fast fluidization, has been known for a long time and is still a subject of ongoing scientific investigations [5 to 10]. With increasing the fluidization velocity up to the turbulent or fast fluidization regime, the bed material will be distributed over the full height of the gasifier, as displayed in the overview on possible fluidization regimes in Figure 2 (merged figure from [10 to 12]). This is important because solids also act as catalysts for tar destruction in gasification systems or directly as the reactant, for example dolomite/limestone with selective transport of CO_2 [13, 14]. The in situ removal of CO_2 out of the gasification reactor generates a hydrogen rich product gas with increased gas quality and higher specific energy content. To be able to work with fine additives like dolomite/limestone powder or other active substances, a dual circulating fluidized bed (DCFB) system with solids separators in the flue and a product gas line is also favorable [15].

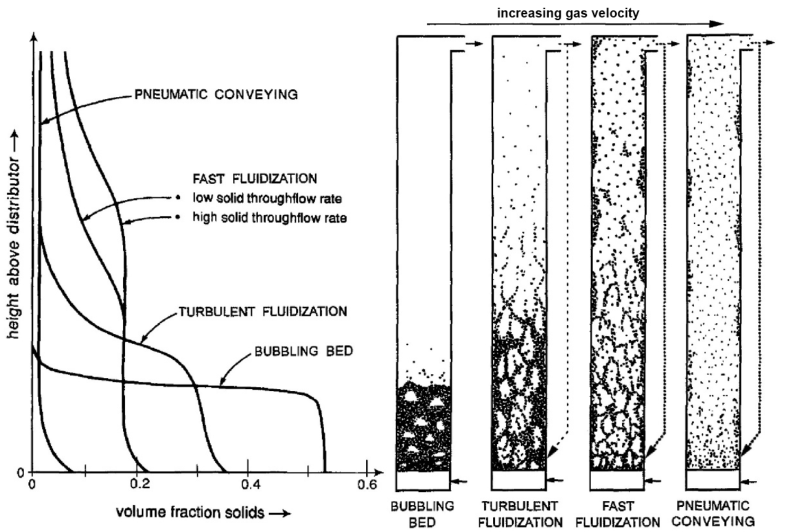

Fig.2: Distribution of solids in various gas–solid fluidization regimes

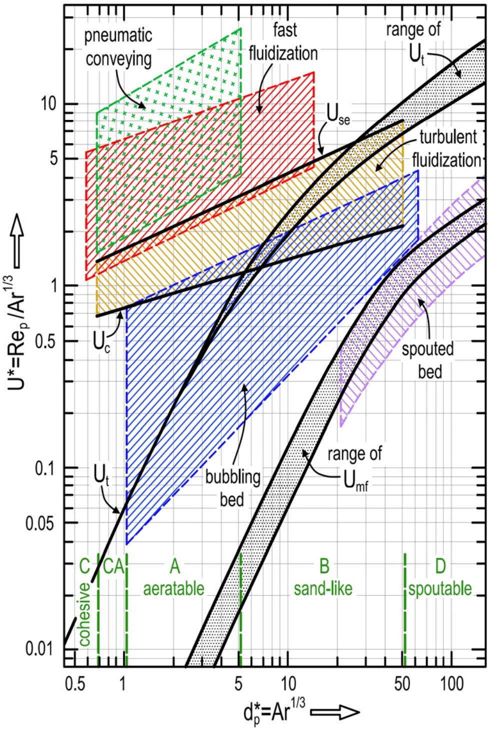

Fig.3: Generalized regime map of gas–solid fluidized beds with typical operation regions of industrial reactors. Regime map: Grace (1986), $U_t(\phi=0.8$ to $1.0)$: Haider and Levenspiel (1989), U_c&U_{se}: Abba, Bi, Grace and Thompson (2003)

With the help of calculated dimensionless numbers it is possible to determine an operation point of a specific fluidized bed in a general regime map. In 1971 Reh presented a meaningful diagram considering the modified Froude-Number (Fr*) on the vertical and the Reynolds-Number (Re_p) on the horizontal chart axes [16]. Grace modified the diagram of Reh in 1986. For this diagram he chose a new arrangement of dimensionless numbers, which are explicit and significant for fluidization velocities (U*) on the vertical and particle diameters (dp*) on the horizontal chart axes [11]. These definitions are useful amendments to the diagram from Reh. The ranges of minimum fluidization velocity (U_{mf}) and terminal velocity (U_t) were integrated into the diagram. Furthermore, regime regions at typical operation modes of industrial fluidized bed reactors can be shown as well. It is possible to present a merged diagram which combines findings of various sources (Figure 3 merged from [11, 17, 18]). The displayed regime areas cover all shown fluidization regimes of Figure 2. It must be taken into account that the boundaries of these detectable regime regions have no sharp limits and the transition is smooth in between. Nevertheless, the clearly arranged boundaries are very useful in interpreting and comparing different operation points during a variation of fluidization velocity or bed material particle sizes. A section of the diagram as shown in Figure 3 will be used subsequently to show different fluidization conditions along the height of a novel reactor design (Figure 9).

There are many ways of obtaining a high quality synthesis gas out of a fluidized bed system. An effective and cheap possibility is to enhance the in situ conversion inside the fuel/gasification reactor in contrast to conventional downstream gas cleaning [19]. Experiments with two existing pilot plants, a $100kW_{th}$ DFB gasifier and a $120kW_{th}$ chemical looping combustion (CLC) plant, at Vienna University of Technology hold that an increase in fluidization velocity increases the effectiveness of gas–solids reactions with significant improvement for the conversion of hydrocarbons [20]. It was also found that the amount of tars is reduced for smaller particle sizes of the bed material. The improvement of tar decomposition can be attributed to the larger surface area of the weakly catalytic bed material and, potentially, also to the higher amount of solids elutriated into the freeboard in the case of operating with small sized bed material and higher fluidization ratios. The aim of the new gasifier concept is an improvement of gas–solid interaction and a long residence time inside the gasification reactor for solids, as well as for the volatiles out of the feedstock. On the one hand, with a fast fluidized bed, solids are distributed over the full height of the gasifier, but with the disadvantages of comparatively high solids' through-flow rates and lower solid density in the whole reactor. On the other hand, typically operated turbulent fluidized beds have very low solids' through-flow rates and higher solid density, but mostly in the lower part of the reactor height. At least it is obvious from the shown solids' distribution profiles (Figure 2) that gas phase conversions will not be supported by gas–solids contact in the practically particle free upper region of a classical bubbling bed gasification reactor. The same scheduled differences have already been described very well by Lewis and Gilliland in 1950 [21]. Thus, the target of the novel gasifier system is to combine the high density zone of the turbulent regime over the full height of the gasification reactor.

3. Design proposal:

A novel fluidized bed reactor system is presented. A new DUAL FLUID concept, the so called "G-volution" gasifier is shown in Figure 4. The fuel/gasification reactor is divided into a sequence of sections. These sections ensure improved gas–solid interaction using flow obstacles in defined height intervals. Gas velocities in the fuel/gasification reactor are chosen in such a way that the final solids' entrainment of bed material is low. Partly elutriated solids at the top are recycled via a cyclone and a loop seal. As recently communicated, the combination of the DCFB concept with flow obstacles leads to a completely new functionality for CFB reactor systems [15, 20, 22].

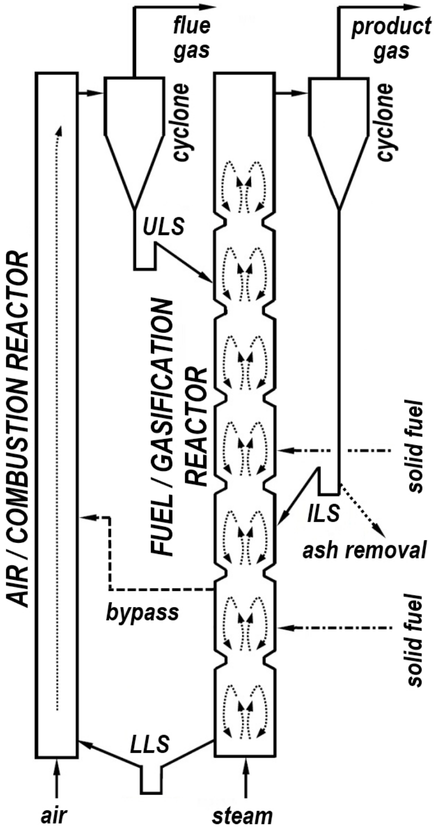

Fig.4: The "G-volution" concept: A novel DUAL FLUID system, (steam fluidized loop seals: ULS=upper loop seal, LLS=lower loop seal, ILS=internal loop seal of gasifier).

4. Experimental:

Fluid dynamics, pressure drops and pressure gradients were investigated with cold flow models (CFMs). The dimensions of the DFB-CLC cold flow model are displayed in Figure 5. To be able to visually observe the influence of the restrictions on flow conditions, a semi cylindrical cold flow model was used. The flow pattern can be observed at the vertical cutting face. In Figure 6 a picture of the semi cylindrical cold flow model is used to explain the fluidization ratios along the height of one of the turbulent zones in the adapted DCFB-CLC cold flow model as shown in Figure 5. A detailed drawing of the DCFB cold flow model is shown on the left of Figures 7 & 8. The DCFB-CFM was used to investigate pressure drops at typical operation modes with ring-type internals in the fuel reactor. The CFM was operated with ambient air and bronze as the bed material with a mean diameter of 160µm.

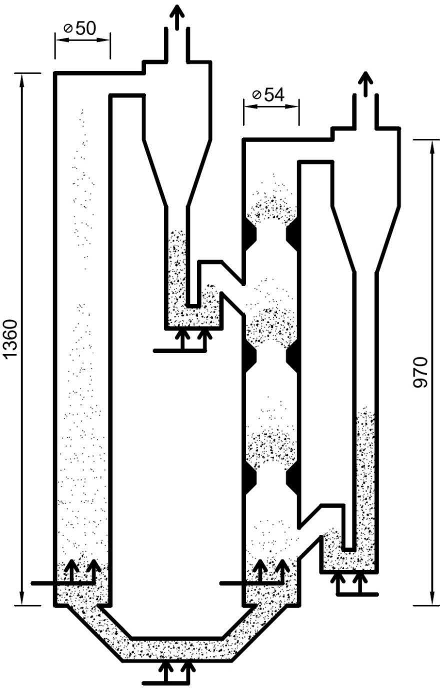

Fig.5: DCFC CLC cold flow model used for investigations

5. Results and Discussion:

Areas with clearly increased solid concentrations normally only occur at the bottom of CFBs with flat walls. Of course, back mixing effects are present in such fluidized bed reactors, but the overall solids volume fraction is typically low, especially in the upper regions of a conventional CFB [7, 8]. In the novel "G-volution" design, an increased solid density is clearly visible in each fluidization zone between the restrictions over the full fuel reactor height of the system. Fluid dynamics in the reactor can be expected to resemble a multistage cascade of stirred vessels. The fuel/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. Based on the CFM results, it is shown that the improvement of gas–solid interaction is significant and the pressure drop increase is acceptable. In Figure 7, the pressure drops of the whole DCFB-System relating to one operation point are illustrated together with a sketch of the adapted CFM. The pressure difference between the lower parts of the combustion and fuel reactor can be used to replace the external combustion reactor fuel input (fuel to CR in Figure 1) by an internal bypass that directs hot product gas, in a defined quantity, from the fuel/gasification to the air/combustion reactor (dashed line in Figure 4). This would not be possible to a great extent at usual operating conditions without ring-type internals, because the pressure inside the fuel reactor is normally lower than in the air reactor [23, 24].

The influences of restricted cross sections in the riser of classical CFBs have already been discussed in different publications [25 to 28]. In contrast, the novel DUAL FLUID system allows a countercurrent gas–solids movement in the same time with nearly constant peaks of pressure gradients over the internals. An easily measurable indicator of uniformly distributed solids fractions in each zone over the whole height of the fuel reactor is investigated. This could represent a desirable operating mode for the new system.

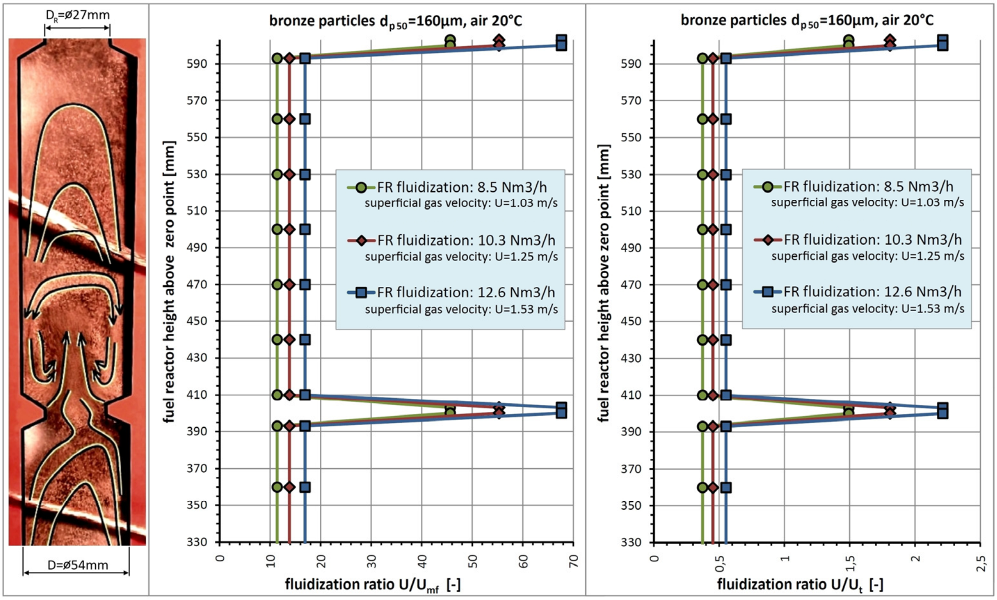

Fig.6: flow pattern and fluidization ratios in the countercurrent gasification reactor, restricted cross section = 25% of free cross section

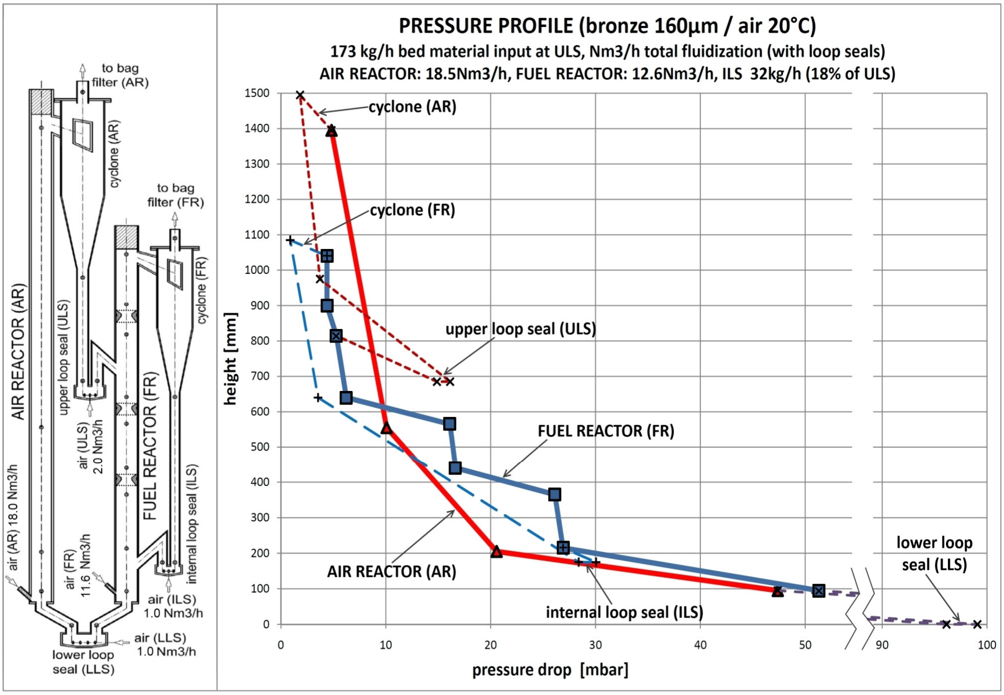

Fig.7: Pressure profile, DCFB cold flow model with internals in the fuel reactor (gasifier)

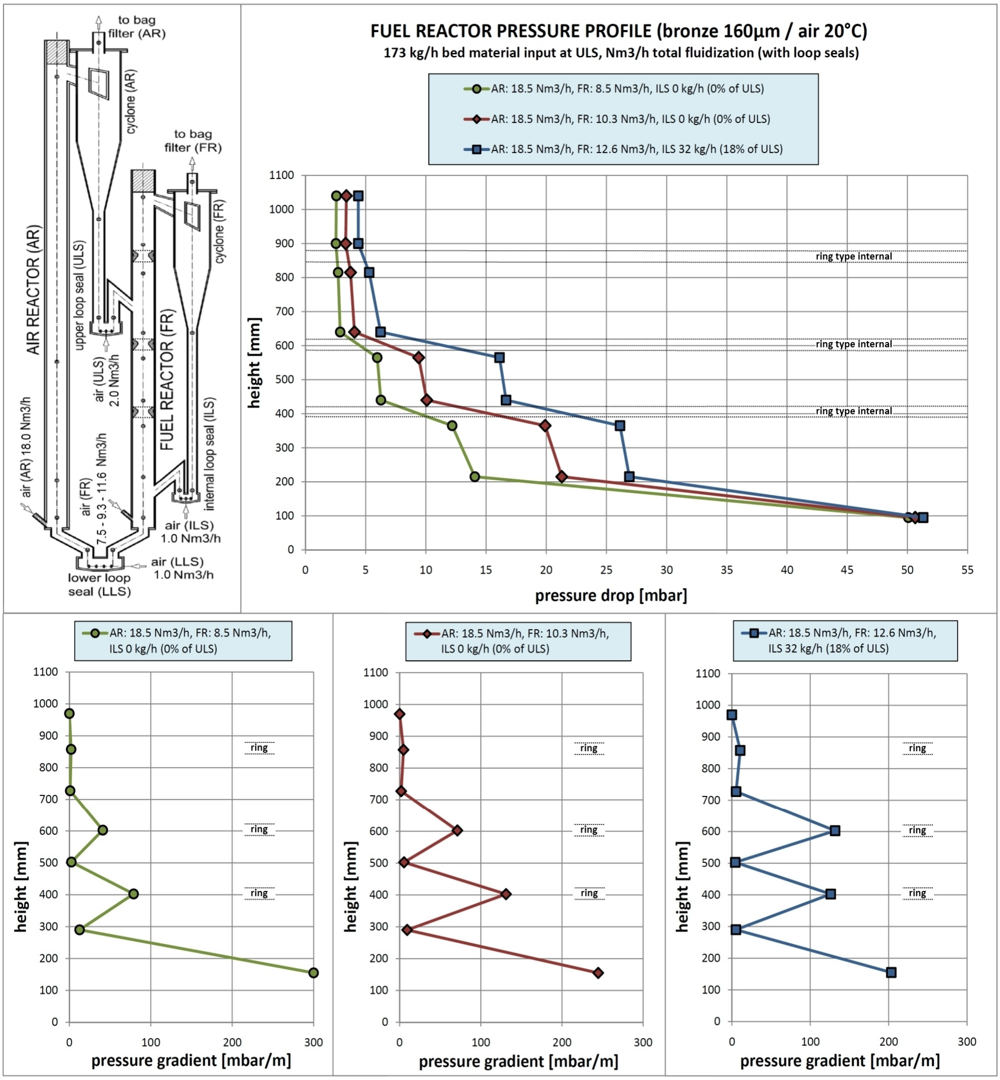

Fig.8: Pressure drop and gradient in the fuel (gasification) reactor of the "G-volution" system

A slight entrainment of solids is given at FR: 12.6 Nm^3/h (U=1.53m/s) in the fuel reactor of the CFM. A further increase of the fluidization velocity leads to significant entrainment of solids from the fuel reactor. The maximum load of the countercurrent reactor is reached. This effect is similar to that of flooding in gas–liquid countercurrent columns flows and is also described for fluidized beds [29, 30]. The results, such as pressure drops and gradients of the fuel reactor and the arrangement of flow obstacles inside the DCFB model with three different fluidization velocities, are shown in Figure 8. Along the reactor height the flow regime of the countercurrent fuel reactor, also called gasification reactor, is typically oscillating from the upper end of bubbling fluidization (free cross section) to the lower end of fast fluidization (restricted cross section). This behavior indicates a turbulent regime between the obstacles. The operation points of the different flow conditions in the fuel/gasification reactor are displayed in the regime map of Grace in Figure 9 (merged from [11, 17, 18]).

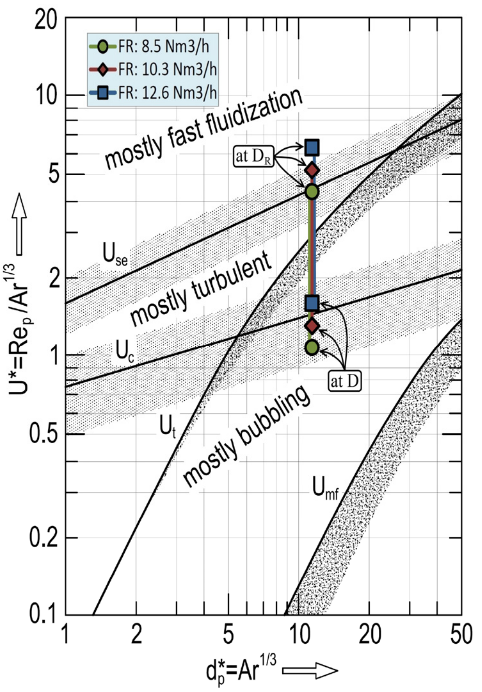

Fig.9: Oscillating flow behavior in the countercurrent gasification reactor (D_R=diameter of restricted cross section, D= diameter of free cross section), Regime map: Grace (1986), U_t (ϕ=0.8 to 1.0): Haider and Levenspiel (1989), U_c&U_{se}: Abba, Bi, Grace and Thompson (2003)

Special arrangements of separator installations, as displayed in Figure 10, allow separate return paths of different solid streams. Fine and light particles will tend to segregate at the top of the staged fuel/gasification reactor while coarse and heavy particles are more likely to move to the bottom. A combination of hard coarse particles for heat transport and softer fines to enhance heterogeneous chemical reactions is possible. As already discussed, the additional recycle possibilities of coarse and fine solids are important options for gasification with selective CO_2 absorption [15].

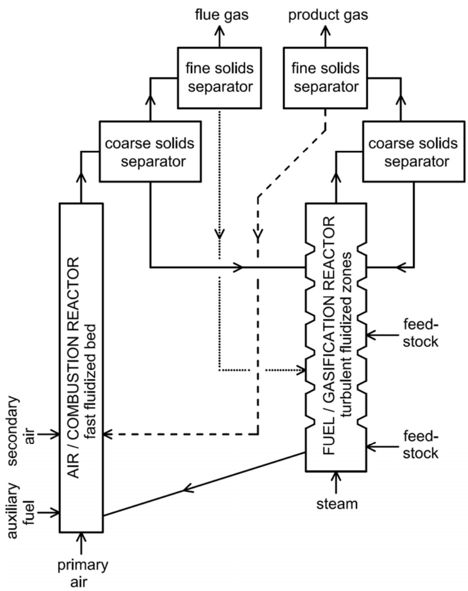

Fig.10: Multistage gas–solid separator arrangement with return paths of coarse and fine solids

6. Conclusion and Outlook

A novel fluidized system with two reactor units interconnected with circulating solids is presented. The global solids loop starts in the air/combustion reactor where solids are entrained, then separated from the gas and sent to the fuel/gasification reactor via a fluidized loop seal. From the fuel/gasification reactor, the solids flow back into the air/combustion reactor via a second loop seal connecting the bottom regions of the two reactors. The solids entrained from the fuel/gasification reactors product gas stream are separated and directed back into the same reactor. Hydrocarbon conversion performance improves with increasing fluidization velocity, possibly due to improved gas–solids contact in a turbulent fluidization regime compared to a bubbling regime. Further improvement in gas–solids contact can be achieved by modification of the geometry in the fuel/gasification reactor. Since the solids leave the fuel/gasification reactor at the bottom a countercurrent flow regime of gas and solids in the secondary CFB is obtained. The fluid dynamics is equivalent to a column of stirred vessels. In addition, the gas phase and the solids have contrary (countercurrent) movements in this part of the system. An increased gas–solids contact in a turbulent regime can be expected. The behavior of the solids, fluidized with varying gas flow rates in the countercurrent reactor, shows a similarity to random-packed gas-liquid columns with a flooding point reached at certain gas flow rates. Several locations of fuel input can optimize reaction conditions and solid feedstock residence time in the fuel/gasification reactor with regard to a wide range of different fuels. Looking at the aspirated turbulent flow conditions in the fuel/gasification reactor and the way the two CFB reactors are connected (loop seals) the innovation of the novel DUAL FLUID system is conspicuous. Furthermore, the proposed design implies conditions where size classification effects take place, which allow selective ash removal. The aim of ongoing research at Vienna University of Technology is to investigate this promising approach at relevant operating conditions for a scale-up to industrial plant size. In order to verify functionality of the proposed system, a new cold flow model is being designed and built according to scaling criteria for fluidized bed reactors [11, 16, 31, 32, 33]. Based on the experimental results, an optimized design for a $100kW_{th}$ to $200kW_{th}$ "G-volution" pilot gasifier is being developed.

7. Acknowledgements

This work is part of the project G-volution and G-volution II under the "New Energies 2020" calls of the Austrian Climate and Energy Fund processed by the Austrian Research Promotion Agency (FFG). The work has been accomplished in cooperation with "TECON Engineering GmbH".

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