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Investigations of solids inventory and particle size distribution in a pressurized circulating fluidized bed combustor

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Abstract: In this article the first results of the extraction of solids inventory by a special sampling system during operation of a pressurized circulating fluidized bed combustor, which has been built in the laboratory of the Institute for Thermodynamics and Energy Conversion at Vienna University of Technology, are presented. A sampling system for granular bulk material makes it possible to take samples discontinuously out of the riser, the return leg and the storage tank below the secondary cyclone during operation. Experience with, especially circulating fluidized beds shows, that the key parameter for successful plant operation is the control of the size distribution of the solids inventory material. During operation the composition and size distribution of inventory material changes due to several physical and chemical phenomena, taking place continuously in the furnace. If the size distribution of the inventory material differs considerably from the original "design size distribution" the main operating parameters of the fluidized bed reactor can be influenced in a negative way.

Key-Words: pressurized fluidized bed, particle distribution, solids inventory, solids extraction, sampling system

1 Introduction

The development of fluidized bed technology started during the twenties of the last century, when Franz Winkler at BASF in Germany made first experiments in the field of coal gasification using the principle of fluidization. Based on his investigations the first coal gasifiers, following the concept of stationary fluidized beds, were developed. A wide field of application for fluidized bed technology emerged from the big demand for aviation gasoline with high octane number during WWII. This gasoline was produced in FCC-reactors (Fluidized catalytic cracking) using circulating fluidized bed technology. Besides the applications in the field of fuel technology, the concept of fluidization has been used in various fields of process engineering like iron- and steelmaking, food technology, drying and coating processes.

Fluidized beds were introduced to the field of combustion engineering during the 60's of the last century. Especially D. Elliot from BCURA (UK) already recognized the possibilities of pressurized combustion in combination with fluidized beds for power production.

To distinguish between the various types of fluidized bed reactors the following main types are defined:

Stationary fluidized bed:

At stationary fluidized beds the gas velocity is adjusted so, that there exists an identifiable boundary (called bed surface) between the bed zone and the freeboard region above. The bed zone consists of the solids gas mixture and can be divided into a dispersed phase and a solids free bubble phase. The occurrence of a certain bubble phase depends on fluidization parameters like e. g. gas mass flow and diameter of particles. The freeboard zone is more or less free of solid matter, only some particles or agglomerates of single particles are ejected into freeboard region due to the burst of bubbles at the bed surface. This ejection can become intensive if bubble bursting is combined with agglomeration of two (or more bubbles) before reaching the bed surface. From the view of process engineering the concept of stationary fluidized beds is simple, compared to circulating fluidized beds, which are described in the following.

Circulating fluidized bed:

The concept of circulating fluidized bed (CFB) was developed by Gilliland and Lewis (1938) at MIT. Now gas velocity has to be set so, that the main part of solid material is entrained from the bottom zone to the top of the reactor. So the terminal velocity of the particles has to be exceeded by the gas velocity in the riser. At CFBs usually bed- and freeboard-zone can't be distinguished, nevertheless typical solids distribution profiles, with an exponential decay along the riser's height are typical.

Pressurized fluidized beds:

At power engineering combustion under elevated pressure offers interesting advantages. For instance in combination with fluidized beds the thermodynamic favorable combined cycle can be realized. In comparison to classic combined cycles, where gaseous or liquid fuel is required, at pressurized fluidized beds (PFB) solid fuels (coal, biomass) can be used. The currently unsolved problem is the quality of hot gas cleaning, which has to prepare the exhaust gas from the PFB to gas turbine quality. Investigations with different types of ceramic filters have been done. Nevertheless it was not possible to develop an economic hot gas cleaning system with adequate life time up till now.

2 Theoretical backgrounds

Experience with, especially circulating fluidized beds (CFBs) shows, that the key parameter for successful plant operation is the control of the size distribution of the solids inventory material. At the initial start up the inventory material of a CFB usually consists of more or less pure quartz sand with a certain size distribution. During operation the composition and size distribution of inventory material changes due to several physical and chemical phenomena, taking place continuously in the furnace. The most important of these phenomena are:

- Attrition at the particle surface and fines generation
- Fragmentation due to thermal shock, collision or chemical reaction
- Separation behavior of cyclone and ash classifier

Some of these phenomena are illustrated in Fig. 1 [1].

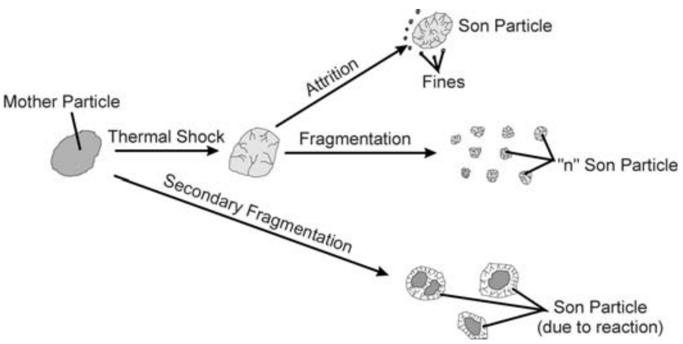

Fig. 1: Attrition and fragmentation

If the size distribution of the inventory material differs considerably from the original "design size distribution" the main operating parameters of the fluidized bed reactor (temperature distribution along the riser, heat transfer to heat exchanger surfaces, chemical reactions (esp. pollutants release and reduction)) can be influenced in a negative way. Additional measures like the installation of an ash mill or the addition of inert material with certain size distribution can become necessary. All these measures are causing costs (for investment in the first case and for deposit at the second example).

From the remarks above the importance of knowledge about size reduction mechanisms in fluidized bed reactors can be deduced and the aim should be to simulate the size distribution of the main components of inventory material (char, inert material and limestone compounds) dependent on the operating parameters of the fluidized bed system. Therefore a comprehensive data basis describing the comminution behavior of solid matter is necessary. The interaction of different phenomena and solid components, both influencing the solids distribution of inventory material, is illustrated in Fig. 2.

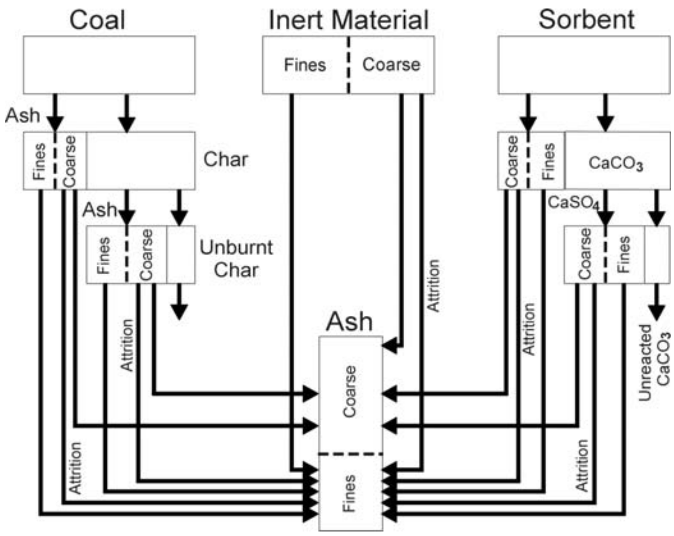

Fig. 2: Fractional mass balances

3 Pressurized circulating fluidized bed (PCFB) system

The PCFB test rig, which has been built in the laboratory of the Institute for Thermodynamics and Energy Conversion at Vienna University of Technology, has been developed to study size reduction mechanisms, which occur to the solids inventory material, to investigate solids distribution and heat transfer and to do research about pollutants release and reduction.

3.1 PCFB test rig

The total system (Fig. 3) consists of the following main components:

- pressure vessel and reactor
- fluidization air supply
- natural gas supply and burner unit
- solid fuel supply
- measuring and controlling equipment

The fluidization air is supplied by two screw compressors (maximum pressure 13 bars) and fed into the pressure vessel, where the PCFB reactor is installed. The test rig can be operated up to temperatures of 850°C. For a constant bed temperature the riser, with an inner diameter of 0,1 m and a height of 4 m, consists of four water-cooled modules. Solid fuel (coal, biomass) and natural gas can be burnt in the reactor. For the combustion of natural gas an own natural gas compressor, which supplies the gas with a maximum pressure of 16 bars to the gas burner unit inside the pressure vessel, has been installed. The suspension carried out of the riser is separated by two cyclones and the solids are recycled to the fluidized bed through an L-valve at the bottom of the standpipe. After leaving the pressure vessel the flue gas is cooled down by water injection and reduced nearly to atmospheric pressure [2, 3].

The volume fractions of solids in the reactor are determined by differential pressure measurements and the temperature distribution along the riser is acquired with a set of thermocouples [4].

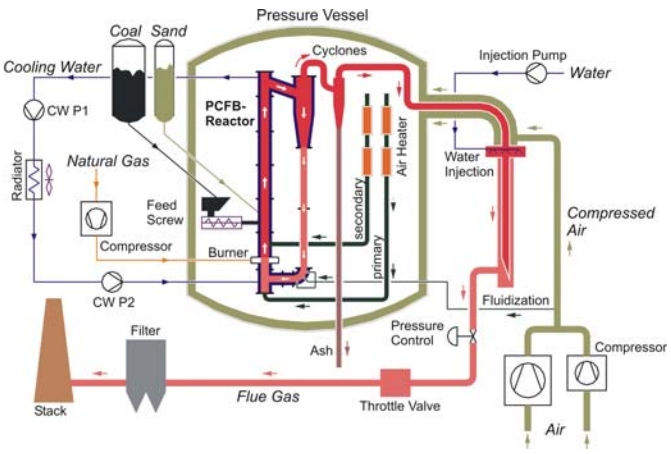

Fig. 3: Scheme of the PCFB system

3.2 Solids sampling system

A special sampling system for granular bulk material has been developed for the extraction of inventory material during the operation of the pressurized fluidized bed boiler under varying operating conditions (up to 13 bars and 850 °C) [6]. By the help of this sampling system, particle size distributions and size reduction mechanisms are to be examined.

The operation of the sampling system (Fig. 4) is effected by a double-acting pneumatic cylinder, which presses a conical nipple against a hardened ferrule. This way of sealing is chosen due to the high temperatures in the fluidized bed.

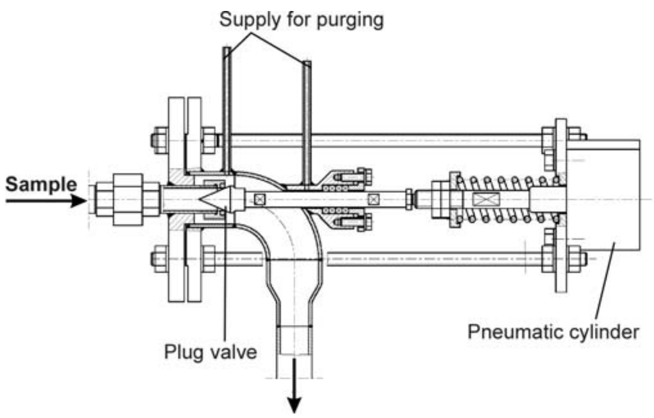

Fig. 4: Pneumatic plug valve

The extraction process can be regulated either by the opening time of the valve or by pressure compensation between reactor and sampling container. For the extraction of a certain mass of solids (0,15 - 0,20 kg) it is more effective to adjust the opening time of the valve.

In order to test the functionality of the sampling device during the operation of the PCFB-reactor, a test rig has been designed and developed in a way that the sampling system can be tested under conditions of ambient temperature. The purpose of this test series was to prove possible separation effects taking also into consideration the influence of certain pressure ratios and pressure stages.

Solids with different densities (silica sand, brown coal) and particle size distributions are mixed by varying the mass ratio. The experiments demonstrate that no significant classification or separation phenomena occurred due to the sampling procedure [5, 7].

4 Experimental work

4.1 Original solids inventory

4.1.1 Silica sand ME 0,71-1,25 mm

This kind of silica sand (Fig. 5) is attrited, washed, sieved and free from lime as well as organic matters (conform to EN 12904).

Fig. 5: Silica sand ME 0,71-1,25 mm

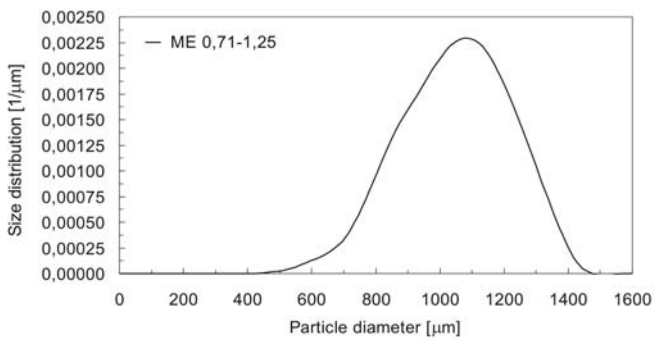

Fig. 6: Size distribution of silica sand ME 0,71-1,25 mm

The size distribution of the used silica sand is shown in Figure 6.

4.1.2 Brown coal

The brown coal from Köflach/Austria (Fig. 7) is dried before feeding by a screw conveyor into the reactor. In Figure 8 the size distribution of the coal, which has an ash content of 26,22 %, is demonstrated.

Fig. 7: Brown coal (Köflach/Austria)

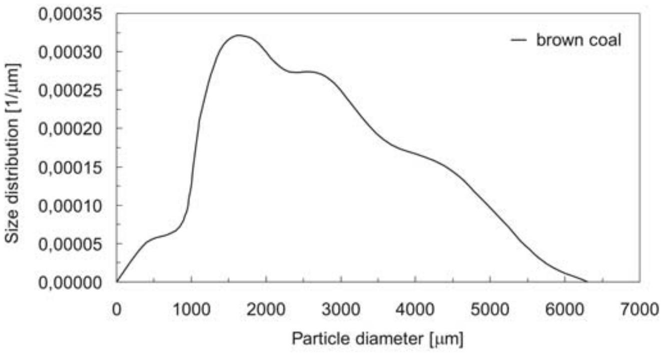

Fig. 8: Size distribution of brown coal

Figure 9 shows the bay-coloured ash with the enclosed stones of the brown coal.

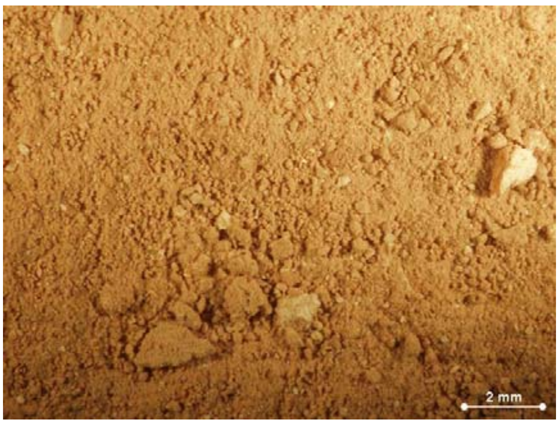

Fig. 9: Brown coal ash with enclosed stones

4.2 Operation of the PCFB system

A start up of the PCFB reactor without inventory mass is required, due to the using of electrical air heaters and an internal gas burner, which is installed in the riser as additional option for combustion and for the setting of excess air during combustion. Single fuel operation, with coal only, is difficult due to the high efforts required to prepare the coal particles (size distribution).

Figure 10 presents some gradients of the temperatures in the riser (T2C, T5, T7) and the standpipe (T1_L, T2_L). The measuring positions are shown in the scheme of the reactor and for better orientation the significant points are marked in the diagram.

After achieving the operating pressure of 5 bars the primary air heaters are started, which increases the temperature up to 400 °C above the distributor.

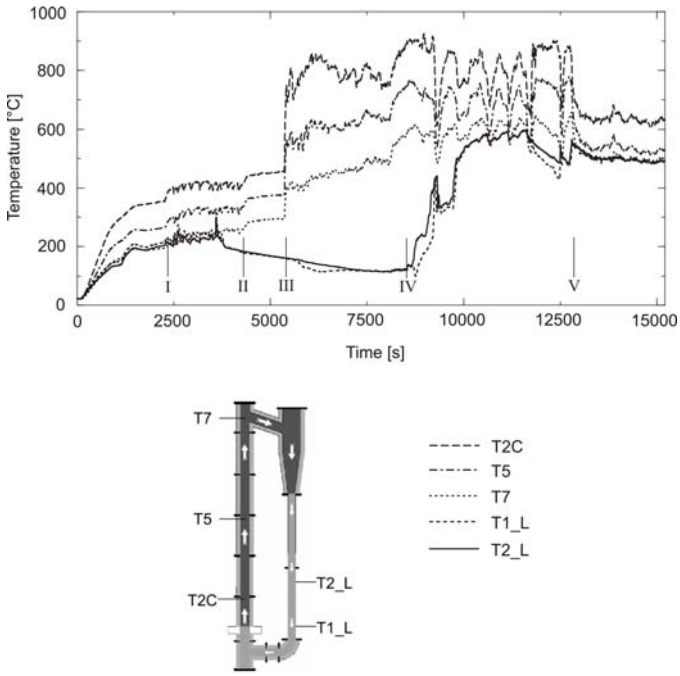

Fig. 10: Gradients of the temperatures

At this time (I) silica sand (ME 0,71–1,25 mm) is fed in portions of 0,2 kg to the system at a superficial gas velocity of 1,8 m/s until a total mass of 2,5 kg is reached. Additionally at time I the coal supply to the reactor is started (brown coal, 1,3 kg/h).Then the coal mass flow is increased to 2,3 kg/h (II) for obtaining the self-ignition temperature of the natural gas. At a temperature level of 530 °C the gas burner was started (III).

After the ignition of the gas the coal mass flow is reduced to 1,3 kg/h. Now the remaining mass of silica sand is fed in steps of 0,5 kg into the reactor, which results in a bubbling bed (IV). Because of the higher temperature the superficial gas velocity increases up to 3 m/s in the riser. For circulating operation the gas velocity has to be enhanced as well as the mass flow of natural gas. The fluidization rate of the L-valve, which can be controlled at three positions (Fig. 3), has to be raised step by step due to the low temperature of the re-circulated solid material. At point V in the diagram the transition to steady circulating operation is finished. The superficial gas velocity is about 3,8 m/s and the fluidization rate of the return leg is set to a value which keeps constant the filling level in the standpipe. Fig. 11 shows the volume fractions of solids after 14500 s.

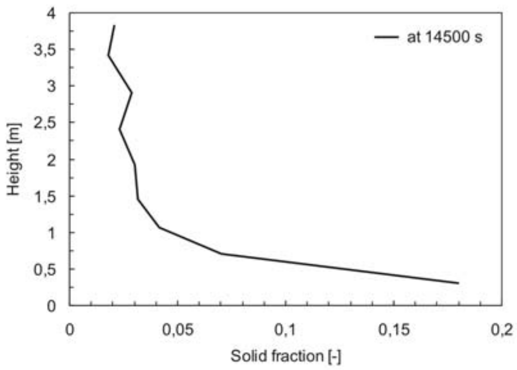

Fig. 11: Volume fractions of solids at 14500 s

4.3 Extraction and analysis of samples

The sampling system for granular bulk material makes it possible to take samples of the solids inventory discontinuously out of the riser, the return leg and the storage tank below the secondary cyclone during operation.

The first extraction from the riser and the return leg was at 13500 s (at that time 4,325 kg of coal were totally fed to the reactor) and the second after 15000 s (riser/return leg 2, fed coal mass 4,865 kg). During the whole experiment a coal mass of 4,951 kg was fed to the test rig.

The samples and the total inventory are analyzed by using a muffle type furnace, a light-optical microscope and sieve analysis (DIN 66165). The determination of TOC was done by ashing conform to DIN 51719.

5 Results and discussion

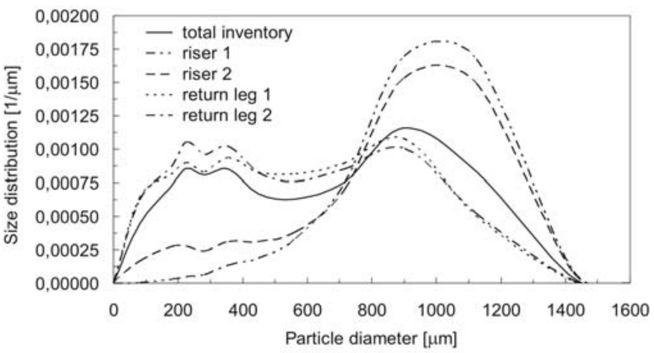

Fig. 12: Size distribution of total inventory and samples from riser and return leg

The size distribution of the total inventory and extracted samples are shown in Figure 12.

The comparison of the size distributions arrives at the conclusion that there is no significant separation or segregation of certain particle size fractions during the sampling procedure under pressurized circulating fluidized bed conditions.

Furthermore a shift to finer fractions (< 600 μm) at increasing time of operation is detected.

Figure 13 and Figure 14 present the extracted samples out of the riser and the return leg at 15000 s (riser/return leg 2).

Fig. 13: Riser 2 (15000 s)

The larger stone in Fig. 13 was enclosed in the brown coal.

Fig. 14: Return leg 2 (15000 s)

The size distribution of the char particles in the total inventory and extracted samples are demonstrated in Figure 15. The bulk of the char particles have a diameter less than 400 μm and none is over 1600 μm.

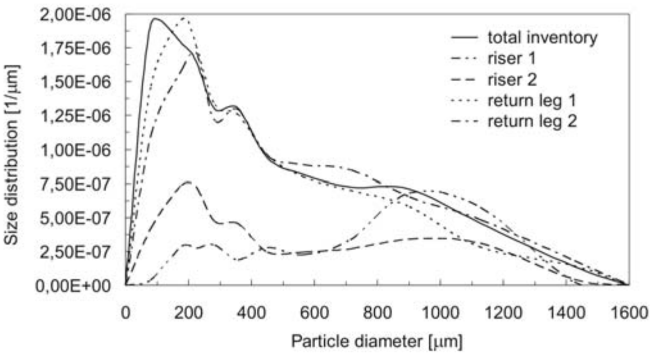

Fig. 15: Size distribution of char particles in total inventory and samples from riser and return leg

In Figure 16 and Figure 17 the separated solid particles of the secondary cyclone with carbon content of 5,32 % before and after ashing are shown.

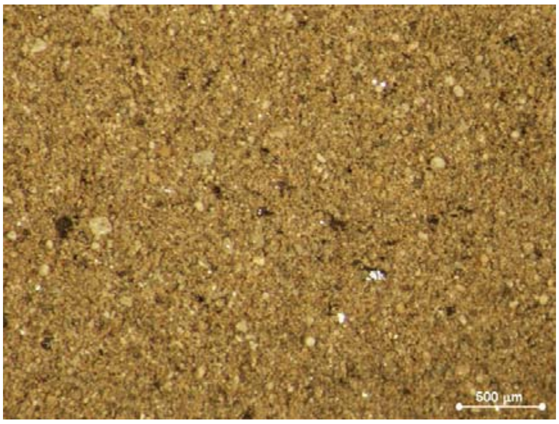

Fig. 16: Particles separated by secondary cyclone

Fig. 17: Separated particles (secondary cyclone) after ashing

6 Conclusion

In this article the first results of the extraction of solids inventory during operation of a pressurized circulating fluidized bed combustor are presented. A special sampling system for granular bulk material makes it possible to take samples of the solids inventory discontinuously out of the riser, the return leg and the storage tank below the secondary cyclone.

The comparison of the size distributions arrives at the conclusion that there is no significant separation or segregation of certain particle size fractions during the sampling procedure. A shift to finer fractions (< 600 µm) at increasing time of operation is detected. Furthermore the bulk of the char particles have a diameter less than 400 µm and none is over 1600 µm.

In the next step the changing of the particle size distribution will be followed for longer operation time of the PCFB system.

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