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CATALYST ATTRITION IN THE CFB RISER

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ABSTRACT

Catalyst attrition in the CFB riser was experimentally investigated in a pilot scale CFB system consisting of a 400 mm diameter riser with a height of 15 m, a return leg and a two-stage cyclone separation. The catalyst loss of the CFB system was measured. In order to discern between attrition occurring in the cyclones and in the riser the system was simulated by a population balance approach which takes the separation efficiency of the cyclone system into account. On the basis of the experimental investigation an empirical correlation for catalyst attrition in the CFB riser has been developed which accounts for the influence of the gas velocity and the catalyst mass in the riser.

INTRODUCTION

Attrition plays a major role in fluidized bed processes where catalyst particles are used, e.g. in the Fluid Catalytic Cracking (FCC) process. In this process the fluidization of the catalyst inside and the transport between the reactors together with the gas solid separation in the solids recovery system (e.g. cyclones) causes a considerable mechanical stress on the catalyst material. This stress leads to particle attrition. In the process a number of attrition sources can be identified. Usually, the gas jets issuing from the gas distributor into the fluidized bed, the bubble motion in the fluidized bed and the cyclones are regarded as the most relevant attrition sources (1). Under normal operating conditions the attrition in a fluidized bed process occurs as surface abrasion, which means that asperities and edges are removed from the surface of particles (2). The primary consequence of attrition is the production of fine particles which can not be kept in the process by the solid recovery system. Thus, attrition leads to a loss of valuable catalyst material (3). Catalyst attrition is therefore a major issue and efforts have to be made to produce sufficiently attrition resistant catalyst in order to reduce the costs for make-up catalyst (4). Furthermore, the prediction of the catalyst loss in a fluidized bed process is an important issue for process design.

Many works deal with the experimental investigation of the attrition sources in a fludized bed process e.g. in the cyclone (5), jet-induced attrition (6) and bubble-induced attrition (7)). At Hamburg University of Technology test procedures were established to characterize the material's attrition propensity under mechanical stress conditions in an isolated cyclone and in a bubbling fluidized bed with and without submerged gas jets.

Based on the experimental investigations of each attrition source in isolation, attrition models have been developed. An overview of various attrition tests is given in (3). Unlike the before mentioned attrition sources, practically no experimental investigation regarding the attrition occurring in a circulating fluidized bed (CFB) riser can be found in the open literature. The difficulty in the experimental investigation of attrition in the CFB riser is that it can not be continuously operated in isolation. This is, because the catalyst which is entrained from the riser with the gas, has to be separated from the gas and returned to the bottom of the riser for continuous operation. Hence, the catalyst loss and changes in the particle size distribution (PSD) in a CFB system will originate from the combination of attrition occurring in the riser and attrition occurring in the cyclone and will be affected by the separation efficiency of the cyclone.

The present work now focuses on the experimental investigation of the attrition occurring in the CFB riser.

THEORY

In this study the attrition occurring in the CFB riser and in the cyclone are considered. The jet-induced attrition occurring above the gas distributor is neglected, because a bubble cap gas distributor with low gas exit velocities is installed in the pilot scale CFB system. Furthermore, the attrition in the return leg is neglected. The catalyst attrition occurring in the cyclone is simulated according to the model developed by Reppenhagen (5). The rate of attrition $r_{\mathrm{c,i}}$ in the particle size class $d_{\mathrm{p,c,i}}$ occurring in the cyclone is given by

$$r_{c,i} = \frac{\dot{m}_{\mathrm{attr,c,i}}}{\dot{m}_{\mathrm{c,in,i}}} = C_{\mathrm{c}} \cdot d_{\mathrm{p,c,i}} \frac{u_{\mathrm{c,in}}^2}{\sqrt{\mu_{\mathrm{c}}}} \tag{1}$$

with $\dot{m}_{\mathrm{attr,c,i}}$ the mass flow of fines generated by attrition in the particle size class i, $\dot{m}_{\mathrm{c,in,i}}$ the catalyst mass flow entering the cyclone, C_{c} is the size-independent attrition rate constant, $d_{\mathrm{p,c,i}}$ the particle size, $u_{\mathrm{c,in}}$ is the gas velocity at the cyclone inlet and μ_{c} is the solids loading of the incoming gas flow,

$$\mu_{\mathrm{c}} = \frac{\dot{m}_{\mathrm{c}}}{\rho_{\mathrm{c}} \cdot u_{\mathrm{c}} \cdot A_{\mathrm{c}}} \tag{2}$$

where ρ_{c} is the density of the inflowing gas and A_{c} is the inlet cross-sectional area of the cyclone.

In contrast to the attrition in the cyclone no specific attrition model for attrition occurring in the CFB is available in the open literature. However, the attrition due to bubble motion in fluidized beds was intensively investigated by various authors. For example Merrick and Highley (7) and Ray et al. (8) found that the bubble-induced attrition rate r_{b}, which is the mass flow of attrition generated fines in the bubbling fluidized bed $\dot{m}_{\mathrm{attr,b}}$ related to the bed material mass m_{b} is given by

$$r_{\mathrm{b}} = \frac{\dot{m}_{\mathrm{attr,b}}}{m_{\mathrm{b}}} = C_{\mathrm{b}} \cdot (u - u_{\mathrm{mf}}) \tag{3}$$

with C_b the attrition rate constant for bubble induced attrition, u the superficial gas velocity in the fluidized bed and u_{mf} the minimum fluidization velocity.

The experimental investigations of the bubble induced attrition, cited above, were carried out at excess gas velocities (u-u_{mf}) below 2.16 m/s (7) and 1.1 m/s (8), respectively. Hence, the application to attrition occurring in a CFB riser, which is operated at much higher gas velocities, means a significant extrapolation. However, as a first approach it is assumed here that the same general relationship describes the rate of attrition occurring in the riser r_r,

$$r_r = \frac{\dot{m}_{\text{attr,r}}}{m_{\text{r}}} = C_{\text{r}} \cdot (u - u_{\text{mf}}) \tag{4}$$

with $\dot{m}_{\text{attr,r}}$ the mass of attrition generated fines in the CFB riser, m_r the mass of catalyst in the riser as indicated by the pressure drop, u the gas velocity in the riser C_r the attrition rate constant for attrition occurring in the CFB riser.

Attrition rates r_c and r_r cannot be measured individually in the CFB loop. What is measured is the overflow of the cyclone which is leaving the system. In order to get access to r_r the population balance for the whole system has to be solved. Therefore, the flowsheeting software SolidSim (9) is used. In SolidSim the system is simulated by connecting unit models for the cyclones and the CFB riser. The CFB riser is modelled by a fluidized bed module developed by Püttmann (10). It accounts for the hydrodynamic as well as the attrition induced changes in the particle size distribution. Based on the population balance modelling approach developed by Werther and Hartge (e.g. 11) the effect of attrition on the PSD in the system is calculated. The attrition process generates fines, which are added to the smallest size class i = 1. Moreover, the mother particles shrink due to surface abrasion, which leads to a mass transfer from the size class i to i-1.

EXPERIMENTAL

Material

In this study equilibrated cracking catalyst (FCC) was used which has been used for long time in the industrial process. The particle size distribution, shown in Fig. 1, has developed from a feed material as result of solids separation and attrition processes. The mean diameter d_{p50} of the catalyst was 85 µm.

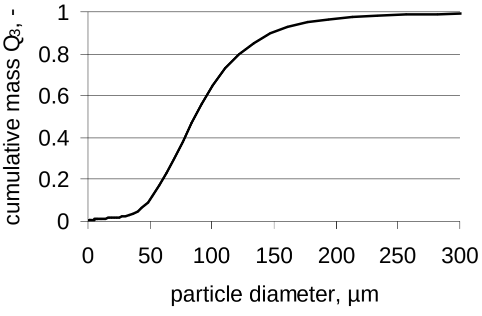

Figure 1. Particle size distribution of the catalyst

Attrition test in an isolated cyclone

The material specific attrition constant C_c for attrition occurring in the cyclone was measured for the FCC catalyst in an isolated cyclone on the lab scale. The diameter of the cyclone was 90 mm. The tests were conducted under ambient conditions with air for gas velocities at the cyclone inlet between 10 and 20 m/s and solids loadings at the cyclone inlet between 1 and 2 kg/kg. Detailed information about the test procedure can be found in (12).

CATALYST LOSS IN THE CFB SYSTEM

The CFB system shown in Fig. 2 was used for the experimental investigation of catalyst attrition occurring in the CFB riser. The riser has a height of 15.6 m and an inner diameter (ID) of 0.4 m. A bubble cap gas distributor is installed. The experiments were conducted under ambient conditions with air as fluidizing gas in the riser and syphon. The cross-sectional average gas velocity in the riser was varied between 3 and 5 m/s and the catalyst mass in the riser between 30 and 110 kg. The catalyst entrained from the riser with the gas is separated by a primary and a secondary cyclone with diameters of 1 m and 0.8 m, respectively. According to the cyclone's separation efficiency some catalyst leaves the secondary cyclone with the gas through the overflow and is then collected in a subsequent bag filter. The latter catalyst is not returned to the process and therefore designated here as catalyst loss. The recovered catalyst is recycled via a syphon to the riser. In the return leg the circulation rate is measured. Therefore, a section of the downcomer is separately supported and decoupled from the system by compensators. In this section a butterfly valve is installed. The circulation rate can be determined by measuring the weight change of the section with time after the butterfly valve is closed.

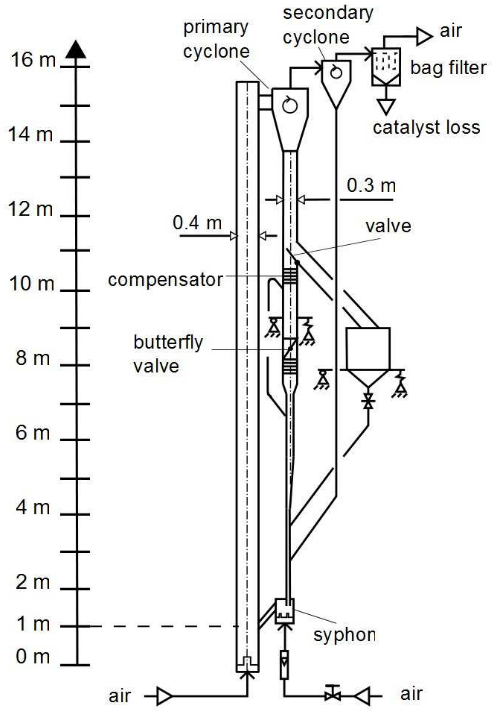

Figure 2. Pilot scale CFB system

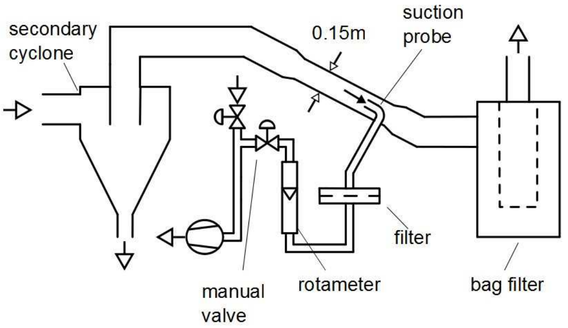

Figure 3. Measurement system

The CFB system's catalyst loss is assessed by measuring a side stream which is withdrawn in a section between the secondary cyclone's overflow and the bag filter. The measurement system used is shown in Fig. 3. The side steam is withdrawn via a suction probe. In the tests two different probes, one with a diameter of 6 mm and the second with a diameter of 20 mm, were used. The catalyst entrained by the withdrawn gas is subsequently separated by a filter. The catalyst mass flow is determined by differential measurement of the filter weight per measurement time. The volume flow through the probe is controlled manually by valves and a rotameter. It is adjusted such that the gas velocity in the probe is the same as the average gas velocity in the measurement section of the pipe. The measurement setup allows the measurement at different radial positions to investigate the solids concentration profile.

RESULTS AND DISCUSSION

Material specific cyclone attrition rate constant

In an isolated cyclone the catalyst loss $\dot{m}_{\mathrm{c,loss}}$, i.e. the catalyst which is entrained with the gas in the cyclone overflow, is measured for multiple passes of the catalyst through the cyclone. Under steady-state conditions it is assumed that the measured $\dot{m}_{\mathrm{c,loss}}$ is equal to the mass flow of fines generated by attrition inside the cyclone and the attrition rate r_{c} is given by

$$r_c = \frac{\dot{m}_{\mathrm{c,loss}}}{\dot{m}_{\mathrm{c,in}}} = C_{\mathrm{c}} \cdot \frac{u_{\mathrm{c,in}}^2}{\sqrt{\mu_{\mathrm{c}}}} \cdot d_{\mathrm{p,c,mean}} \tag{5}$$

with the mean particle size $d_{\mathrm{p,c,mean}}$ defined as

$$d_{\mathrm{p,c,mean}} = \sum_{i=1}^{n} d_{\mathrm{p,c,i}} \cdot q_{3,\mathrm{i}}\, \Delta d_{\mathrm{p,c,i}} \tag{6}$$

q_3 denotes the mass density distribution of the particles entering the cyclone. The mean particle size is calculated with the PSD measured for the FCC catalyst.

In Fig. 4 the attrition rate r_{c} against the passes through the cyclone is shown for two tests at different operating conditions. The results illustrate that the attrition rates measured for the first passes through the cyclone are higher than for the following. This can be explained by fines which are present in the feed material and are sifted off in the first passes through the cyclone. Thereafter the attrition rate decreases to a stationary value, the so called steady state attrition rate indicated by the dashed lines in Fig. 4. The steady state attrition rate measured for each operating condition plotted against the product of $d_{\mathrm{p,c,mean}} \cdot u_{\mathrm{c,in}}^2 \cdot \mu_{\mathrm{c}}^{-0.5}$ is shown in Fig. 5. According to the attrition model equ. (1) the slope of the straight line represents the material specific steady state attrition rate constant C_{c}, which is $8.8 \cdot 10^{-4}$ s²/m³ in this case.

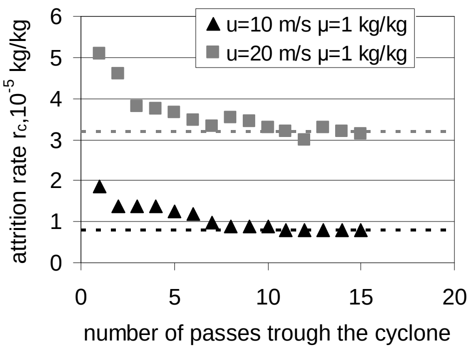

Figure 4. Attrition rates r_{c} measured over 15 passes through the cyclone for two different operating conditions

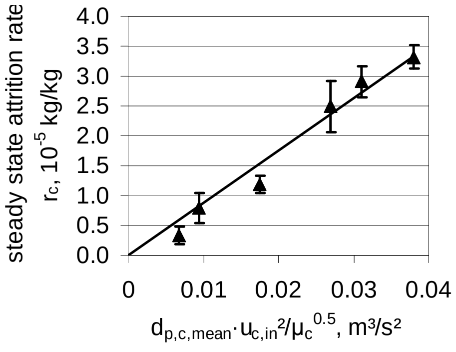

Figure 5. Steady state attrition rates versus the operating conditions according to the attrition model in equ. (1)

Attrition test in the CFB system

The CFB system was operated over 200 h under different operating conditions. For each measurement condition the plant was filled with a predetermined mass of solids (8-200 kg). Then the plant was run for two hours in order to elutriate the fines of the initial inventory. After this time the cyclone loss contains only solids generated by attrition, i.e. the fines attrited from the solids and the particles which have shrunk by attrition. This is a quasi-steady state. A real steady state would require addition of fresh bed material compensating the loss. Since the measurements show that the catalyst loss during one hour is less than 0.05 % of the bed material this latter effect was neglected.

The catalyst mass flow in the side stream of the cyclone is measured using the measurement setup shown in Fig. 3. Under each operating condition the measurement was repeated more than four times. In order to isolate the attrition effect in the riser it must be considered that the measured catalyst loss results from several mechanisms, i.e. attrition occurring in the cyclones, attrition in the riser, particle shrinkage and the separation in the cyclones. The difficulty is that the latter mechanisms are influenced by the catalyst's particle size distribution and concurrently affect the catalyst's PSD themselves. Hence, the CFB system has to be simulated in consideration of the catalyst's PSD.

In Fig. 6 the cross sectional average catalyst mass flow in the riser G_s measured for the three different gas velocities versus the catalyst mass in the riser is shown. Obviously, the circulation rate increases with increasing gas velocity and catalyst mass in the riser. The G_s values measured under different operating conditions vary from 15 and 60 kg/m²s.

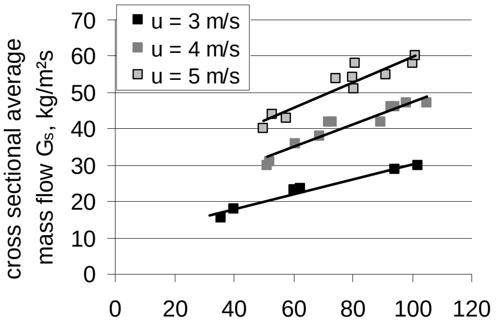

Figure 6. Influence of the catalyst mass and gas velocity u on the cross sectional average solid mass flow in the riser G_s

Simulation

The simulation flowsheet representing the pilot scale CFB system is shown in Fig. 7. The process is simulated based on the catalyst properties (i.e. PSD and attrition characteristics), the operating conditions and the geometry of the CFB system.

Unlike the attrition constant C_c the constant for attrition occurring in the riser C_r (c.f. equ. (4)) is unknown. Hence, this parameter is fitted to all measurements using the simulation. The material specific attrition constant C_r is found to be $3.2 \cdot 10^{-8}$ 1/m. Compared to the attrition rate constants for FCC catalysts measured previously in a stationary fluidized bed $C_b = 0.45 \cdot 10^{-8}$ 1/m and $C_b = 1.37 \cdot 10^{-8}$ 1/m (12) the attrition rate constant C_r is higher.

The exemplary result for the simulation conducted with a catalyst mass in the riser of 89 kg and a superficial gas velocity in the riser of 4 m/s are also shown in Fig. 7. The results display that attrition in the riser is responsible for a major part of the catalyst loss. The rate of attrition occurring in the riser r_r, operated at a superficial gas velocity of 4 m/s is 1.1 % of the catalyst inventory in the riser per day.

The influence of the catalyst mass in the riser on the catalyst loss rate was experimentally investigated. Additionally, simulation runs with varying catalyst mass in the riser are conducted. A comparison between the measured and simulated catalyst loss rate is shown Fig. 8. The catalyst loss rate increases with increasing catalyst mass in the riser. The influence of the gas velocity in the riser on the catalyst loss rate is shown in Fig. 9. The gas velocity has a significant influence on the catalyst loss rate in the CFB system, with increasing gas velocity in the riser the catalyst loss increases. The results indicate that with the approach for attrition in the CFB riser, equ. (4), a satisfactory description of all measured values is possible.

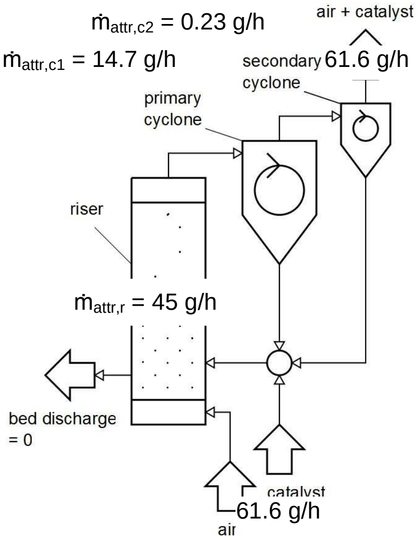

Figure 7. SolidSim flowsheet representing the CFB system with simulation results for m_r = 89 kg and u = 4 m/s

CONCLUSION

The catalyst loss of a pilot scale CFB system was measured. The influence of the catalyst inventory in the riser and the gas velocity in the riser was investigated. Based on a population balance approach the attrition in the CFB system was simulated. The simulation considered the attrition occurring in the cyclone and in the CFB riser in the mode of pure abrasion. As a first approximation the mass produced by attrition in the riser was assumed to be linear proportional to the excess gas velocity (u-u_{mf}) and the solids mass m_r in the riser, respectively. The attrition constant for attrition occurring in the CFB riser was then fitted to the measured values using the simulation. The

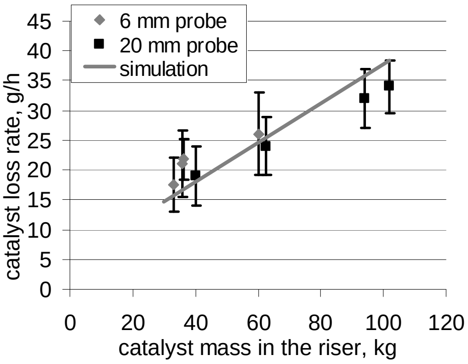

Figure 8. Influence of the catalyst mass in the riser on the catalyst loss rate for u = 3 m/s

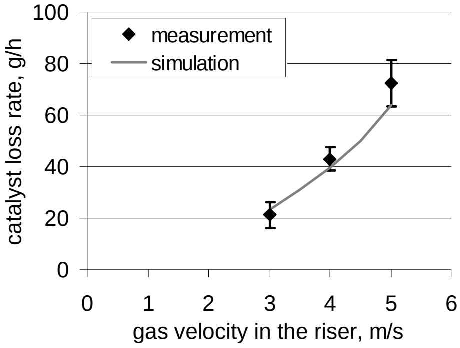

Figure 9. Influence of the gas velocity in the riser on the catalyst loss rate for m_r = 50 kg

comparison of the simulation results and the measured catalyst loss rates for varying solids mass in the riser and gas velocities indicates that the simulation predicts the tendencies without significant deviations. Additionally, the simulation allows the investigation of the individual attrition sources.

NOTATION

A_c	cross-sectional cyclone inlet area, m^2	q_3	mass density distribution, 1/m
C_b	bubble induced attrition constant, 1/m	r	attrition rate, r_c, - ; r_b and r_r, 1/s
C_c	constant for attrition occurring in the cyclone, s^2/m^3	$u_{c,in}$	gas velocity in the cyclone inlet, m/s
C_r	constant for attrition occurring in the CFB riser, 1/m	u_{mf}	minimum fluidization velocity, m/s
d_p	particle diameter, m	μ_c	solids loading of the gas, kg/kg
G_s	average cross sectional solids mass flow in the riser, kg/m^{2}s	ρ_c	gas density at the cyclone inlet, kg/m^3
$\dot{m}$	mass flow, kg/s	CFB	circulating fluidized bed
m	mass, kg	PSD	carticle size distribution

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