# Separation Efficiency of Recirculating Cyclones in Circulating Fluidized Bed Combustions

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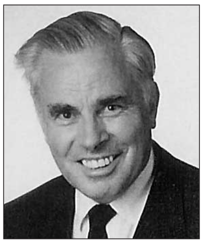

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## Introduction

Figure 1 shows a scheme of a circulating fluidized bed (CFB) combustion for burning coal: The main part of the burning air is injected at the bottom of the furnace. Together with the very fine lime particles and the solids, recirculated into the combustor by the cyclones, a stable fluidized bed of small height is built. Out of this fluidized bed a mixture of air and flue gas streams to the top of the combustor with velocities between 5 and 10 m/s, carrying a load

$$\mu = \frac{\dot{M}_S}{\dot{M}_{Gas}} = 1 \ldots 20 \, \frac{\text{kg/s solids}}{\text{kg/s gas}} \qquad (1)$$

of soilds to the closely attached cyclones. The solids in the circulating mass are mainly fly ash mixed with a small amount of partly burned coal and lime, their particle sizes cover a range between $d_{min} \approx 5$ µm and $d_{max} \approx 500$ µm. The temperature in the bed is only about 850 °C, which is the optimal reaction temperature for desulphurization in the bed. At this temperature the combustion is running slowly but stable. The combustion is completed after 10...100 circulations. The pressure is typically around 1 bar.

Heat is extracted in different ways, depending on the boiler type. In the most important basic types this is done a) by radiation at the combustor wall or at heat transfer surfaces in the furnace (Lurgi – and Ahlström/Pyropower-system), or b) in an external fluidized bed cooler (Lurgi-system, see Figure 1), or c) by cooling the total ash mass flow by an evaporative cooler in the upper part of the furnace below 500 °C (Circofluid-system of Babcock).

The mass flow rate (MFR) and the particle size distribution (PSD) of the circulating solids in a CFB-boiler strongly determine the heat transfer as well as chemical reactions. MFR must be large enough and PSD sufficient fine to obtain an optimal performance of the boiler. Both quantities depend strongly on the collection efficiency of the cyclones.

Already small reductions of the cyclone efficiency by less than 1 % lead in particular to a considerable lack of inert material, which serves as a heat storage in the boiler. Then the heat transfer is inefficient. Other consequences are losses of burnable material or an unstable operating behaviour of the boiler, especially with respect to the furnace temperature.

In many plants the missing inert material is compensated by adding large amounts of sand, which is very expensive and leads to additional erosion problems.

During the last years the cyclone efficiency has been improved in several large commercial CFB power plants by small changes of the cyclone geometry [1 to 4]. In the present contribution these measures are presented. Furthermore the relation between a cyclone improvement and its effect on the ash inventory of the boiler is estimated quantitatively. This leads to a quantitative understandig of the results in the modified large plants. It also makes transparent the enormous importance of an optimal cyclone operation behaviour for a good boiler performance.

## Methods for Improving CFB-Cyclones

### Acceleration of Particles in the Entrance Duct

Cyclones in CFB-power plants are usually located very close to the furnace. Therefore the entrance duct between the furnace and the cyclone is mostly short with a typical length of 2 up to 4 m. This length is normally not sufficient to accelerate the solids, starting at the beginning of the duct with a horizontal velocity of nearly 0 m/s onto the full gas velocity $v_e$ at the end of the duct, which is usually about 20 to 25 m/s. Calculations, based on the theory of pneumatic conveying [1, 5 and 6] as well as measurements in industrial plants (see Figure 3 and [7]) and in pilot plants [8] show that the solids velocity $c_e$ at the end of the duct is usually only (0.5 to 0.8) · $v_e$. If the solids velocity $c_e$ is considerably less than that of the gas flow $v_e$, immediate exchange of momentum between solids and gas takes place in the entrance zone of the cyclone until gas and solids have the same velocity. This leads to a remarkable deceleration of the gas flow within the entrance zone. The flow therefore spreads in the cyclone.

Figure 2 shows the calculated particle- and gas velocities c(l) und $\nu(l)$ in a dimensionless plot for a duct with constant cross-section, for $d_{50} = 50$ µm and $\mu = 5$, for the gas density $\rho_{Gas} = 0.32$ kg/m$^3$ and for the gas viscosity $\eta_{Gas} = 45 \cdot 10^{-6}$ Pa · s. The gas velocity in the duct is $\nu_{duct} = 22$ m/s, and L = 1 corresponds to the length l = 2.2 m.

A more accurate calculation takes into account the decrease of the loading µ and of the mean particle size $d_{50}$ as well as the increase of gas – and particle-velocity $\nu$ and c from the bottom to the top of the duct, which has been measured [7] (Figure 3). For details see [1].

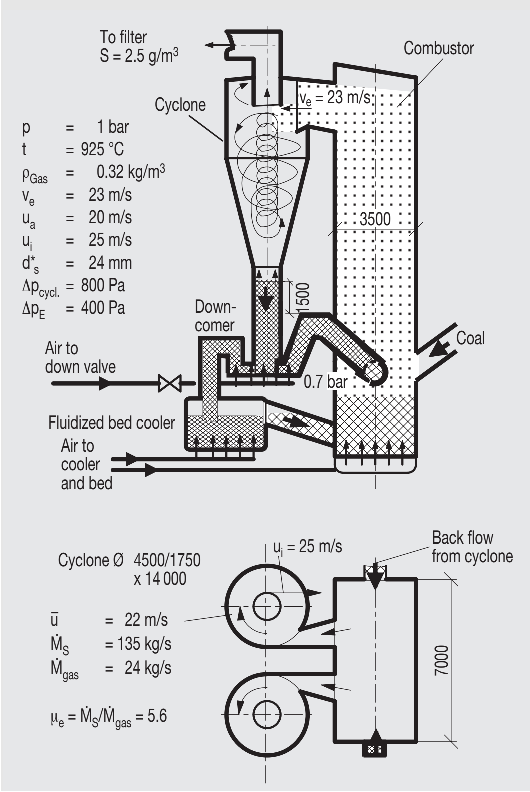

*Figure 1. Circulating fluidized bed combustor (dimensions in mm).*

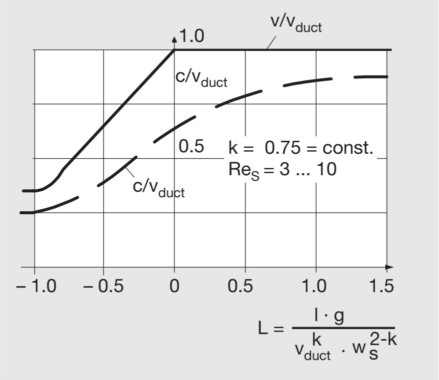

*Figure 2. Example for dimensionless graphs of gas- and particle-velocities before (L < 0) and in (L > 0) an entrance duct to a recirculating cyclone.*

### Boundary Layer Around the Vortex Finder

The flow around the vortex finder (VF) is laminar because of the very stable stratification of the boundary layer. That layer is without any driving power by exchange of momentum with the outer circulating flow. The boundary layer is 5 to 10 % of the main flow through the cyclone. It comes from beyond the cover as secondary flow, takes 10 to 20 g/m$^3$ dust with it and is going in steep spirals to the VF, where it is deflected downward and circulates around the VF. Along its way around the tube the boundary layer is thickening considerably at angles between 150° and 290° measured from the end of the entrance duct [9, 10].

The reason for this behaviour of the boundary layer is that the entering jet behaves as a strong disturbance on the rotating gas flow, which leads to an unsymmetrical distribution of the boundary layer around the VF.

### Improvements

### *Excentrical Position of VF*

*M. Trefz* tried to improve the very unsymmetrical flow of the boundary layer around and along the VF by shifting the tube in an excentrical position (Figure 4b). Then all stream lines of the boundary layer around the VF are parallel and oblique on the wall, more or less (Figure 5b), i.e. there is no flow without any tangential velocity, as it is the case for centrical position of the VF (Figure 4a). The stream lines shown in Figure 5 have been made visible by injecting ink at the top of the outer VF wall. The excentrically located VF thus prevents a detachment of the flow and increases the cyclone separation efficiency [9, 10 and 2].

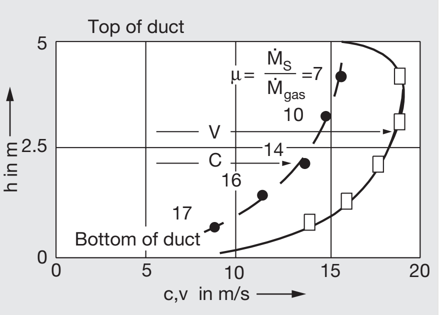

*Figure 3. Measured gas- and particle-velocities in a short entrance duct (1.35 m × 5 m) to a recirculating cyclone (Bayer 1985).*

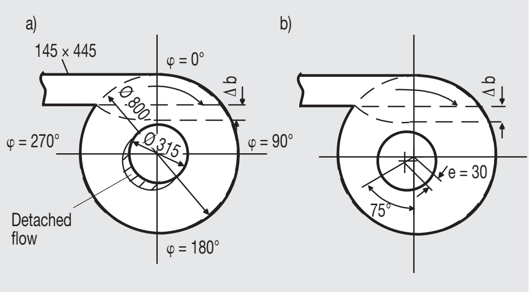

*Figure 4. Cyclone with a) centrical and b) excentrical vortex finder.*

### *Special Shape of Entrance Duct*

Part of the incommodity of excentrically positioned VF can be avoided if the short entrance is formed in a special way: At the beginning the entrance duct could be of nearly square cross-section and should change to a narrow rectangle with the ratio height to width of a : b ≈ 3 : 1 up to 4 : 1 with downward inclined bottom of about 30°. On behalf of that special shape the solids velocity at the end of the duct will be increased without enhancing the gas velocity at that point. This effect is achieved by a strong particle acceleration at the beginning of the duct in such a way that the particles reach the gas velocity at the end of the duct. The gas flow will be delayed along the duct, starting with about 20 m/s and slowing down to about 15 m/s. The decelerated flow remains steady without detachment from the wall as long as the static pressure will not rise. No deposition would occur on the downward going bottom of the duct. Wear and abrasion in the duct as well as in the cyclone would be suppressed on behalf of the fairly low velocities [1].

## Measurements in a Pilot Plant

In 1996 measurements in a pilot plant, installed in the CFB power plant of Wuppertaler Stadtwerke, have been performed with the aim to test the effect of an excentrical shift of the insert onto the cyclone separation efficiency at high loadings.

### *Set-Up*

The test cyclone, which is a 1 : 7.5 plexiglass model of a big cyclone in the CFB power plant Wuppertal, has a diameter of 610 mm and is operated with cold air (20 °C). To simulate the physical conditions in the real cyclone the gas velocity is adjusted between 4 and 6 m/s and the particle size of the test powder (= quartz sand) with $d_{50}$ = 40 μm. At these values the Froude number $F^* = v^k \cdot w_{S,0}^{2-k}/(D \cdot g)$ in the real and in the test cyclone are the same. The Froude number depends on the variables v = gas velocity, $w_{S,0}$ = settling velocity of a single particle, D = typical duct width and g = 9.81 m/s$^2$. The exponent k depends on the particle Reynolds number and has values between 0.5 and 1. The supply of the solids is controlled by a slide above the outlet of a silo. From the outlet of the silo the solids are conveyed pneumatically by pressurized air over a horizontal ramp into the entrance duct of the cyclone. This method provides for a horizontal and steady mass flow at the beginning of the entrance duct as it is the case in the real plant. The solids load μ is varied between 0.5 and 12. In the big plant the dust load of the flue gas into the cyclone is μ ≈ 7.

The insert with a diameter of 230 mm and length of 185 mm can be shifted. Two collars of diameter 280 and 310 mm respectively and with a height of 70 mm can be installed at the cover of the cyclone around the insert.

### *Results*

In Figure 6 the measured separation efficiency η of the cyclone is shown as a function of the solids load μ for different insert arrangements:

By an excentrical shift of the insert (black symbols) of e = 15 and 25 mm respectively at an angle of the shift of 210° and 230° respectively (measured from the end of the entrance duct) the separation efficiency is improved at higher loadings between 5 and 10 by 0.3 to 1 %, compared to the centrical insert position (white symbols).

For the centrical insert neither a collar centrically installed nor a collar excentrically installed around the insert leads to an increase of the separation efficiency.

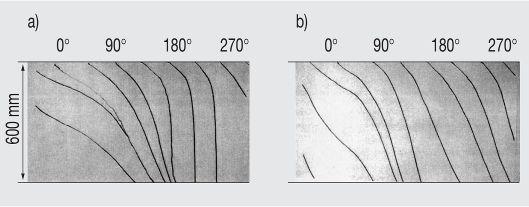

*Figure 5. Stream lines (made visible by drops of ink) of boundary layer along outer wall of vortex finder of cyclone in Figure 4 in the angle range 0 to 360° for a) centrical and b) excentrical vortex finder.*

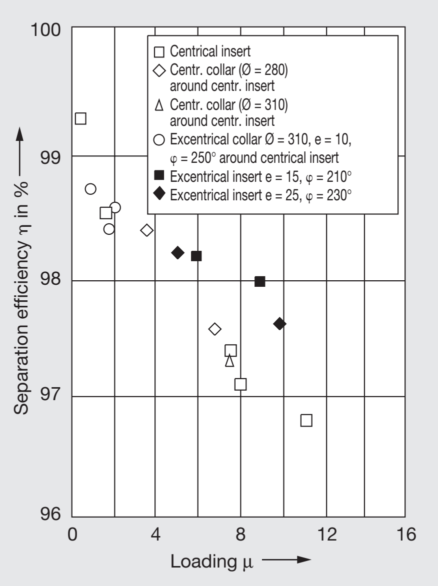

*Figure 6. Measured separation efficiencies of test cyclone at Wuppertaler Stadtwerke for various insert arrangements (1996).*
Cyclone Ø = 610 mm
Insert Ø = 230 mm

## Applications in Commercial Power Plants

Cyclone improvements according to the concepts explained above have been performed in eight large commercial CFB boilers with thermal capacities between 55 and 550 MW. In the following these modifications and their effects on the boiler performance will be presented. In Tables 1 and 2 the results are summarized and complemented with additional data.

Power Plant Energieversorgung Offenbach/Boiler DE 11

Modifications:

- cyclone entrance zone: Threshold in duct, elongation of duct, modification of bottom of entrance spiral,
- vortex finder: Excentrical shift and narrowing, swirl vane insert for pressure recovery,
- cyclone cone and downcomer: Chinese hat in lower conical part, injection of pressurized air into downcomer to avoid blocking due to increased mass flow rate.

Power plant Energieversorgung Offenbach/Boiler DE 12

Modifications:

As in DE 11, but without the modifications in the area of the cyclone inlet.

*Results*

Both boilers DE 11 and DE 12 show a more stable operating behaviour after the modification: When equilibrium state is reached no further intervention for regulating the bed temperature was neccessary. The bed temparature now moves within a small band of 5 to 10 °C. At constant load, removing of cyclone- or filter ash from storages is no longer required. These improvements are due to a strong increase of the solids circulation rate.

The measured particle size distribution curves of the cyclone- and of the filter-ash show much less scattering than before modification, see Figures 7 and 8. Thus the cyclone separates clearly sharper than before and is on the whole more efficient. On the other hand the range of particle sizes with a mean particle size of about 100 µm for cyclone ash and about 25 µm for filter ash has not changed considerably.

The thermal efficiencies of both boilers have been improved by 2 to 3 %. According to the operator's estimation 1 to 2 % is due to the cyclone improvement and 1 to 2 % is due to the application of artificial sound generation in the boiler.

*Differences Between Boiler DE 11 and Boiler DE 12*

The mean particle size of cyclone ash in DE 11 is somewhat finer ($d_{50}$ = 95 µm) than in DE 12 ($d_{50}$ = 110 µm). Before the modification the situation was vice versa (Figures 7 and 8).

Furthermore it has been observed that the bed ash in DE 11 contains distinctly more cyclone ash than the bed ash in DE 12, under the same operating conditions. This leads to the conclusion that the solids circulation rate in DE 11 is higher than in DE 12.

*Conclusions*

- The excentrical shift and narrowing of the vortex finder leads to an increase of the cyclone separation efficiency resulting in a strong augmentation of solids circulation rate.
- Since both boilers DE 11 and DE 12 are identical apart from the geometry of the cyclone entrance region, and since both are operated under the same conditions with the same coal, the observation of a higher solids circulation rate in DE 11 leads to the conclusion that the cyclones in DE 11 separate more efficiently than those in DE 12. This is due to the differences in the geometry of the cyclone entrance region (duct, bottom of entrance spiral).

*Table 1. Cyclone improvements in 4 CFB power plants and their effects on the boiler performance.*
*Values marked with $^1$ are calculated, all others are measured.*

| Power plant | Energieversorgung Offenbach | | Rheinbraun Berrenrath | Rheinbraun Wachtberg |
|---|---|---|---|---|
| | DE 11 | DE 12 | | |
| Technical data | | | | |
| Steam generation t/h | 110 | 110 | 250 | 175 |
| Fuel | Hard coal | Hard coal | Brown coal | Brown coal |
| Number of cyclones | 2 | 2 | 2 | 2 |
| Cyclone diameter mm | 3120 | 3120 | 6290 | 5330 |
| Modifications | Insert excentr. shifted, narrowed and shortened;<br>Injection of pressurized air in downcomer;<br>Threshold in duct and onto bottom of inlet spiral:<br>Elongation of duct | Insert excentr. shifted, narrowed and shortened;<br>Injection of pressurized air in downcomer | Insert excentr. shifted, narrowed and elongated | Insert excentr. narrowed at its lower edge and elongated |
| Insert diameter mm | 1704 → 1450 | 1704 → 1450 | 2830 → 2480 | 2200 → 1900 |
| Excentrical shift mm | 0 → 40 | 0 → 40 | 0 → 150 | 0 → 200 |
| Angle of excentr.shift ° | 240 | 240 | 230 | 230 |
| Insert length mm | 2900 → 2600 | 2900 → 2600 | 830 → 1670 | 600 → 1000 |
| Results | | | | |
| Loading of circulating ash | 1.6 → (2 ... 3)$^1$ | 1.6 → (2 ... 3)$^1$ | 9 → (12 ... 15)$^1$ | 8 → (11 ... 14)$^1$ |
| Adding of sand or ash from silos in t/h | reduced to 0 | reduced to 0 | 20 → 8 | (10 .. 15) → 2 |
| $d_{50}$ of circulating ash in µm | 110 ± 40 → 95 ± 25 | 100 ± 50 → 110 ± 25 | 160 → (140 ... 150)$^1$ | 175 → (150 ... 160)$^1$ |
| Operating behaviour | Operating behaviour more stable, thermal efficiency increased, return of ashes from silos into furnace for controlling bed temperature no longer neccessary | | Operating behaviour more stable with sharp reduction of sand addition | Operating behaviour more stable with sharp reduction of sand addition |

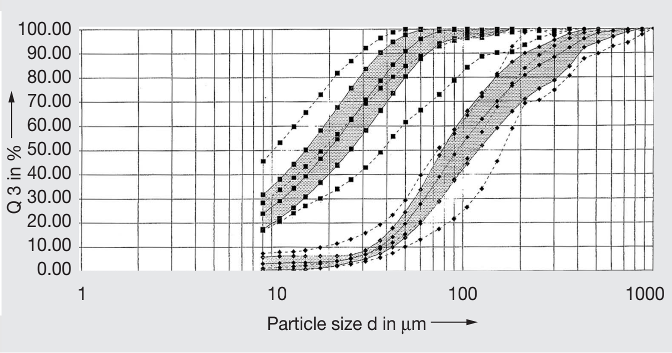

*Figure 7. Power plant EVO/Boiler DE 11/Filter- and Cyclone ash particle-size distribution curves before (dashed lines) and after (full lines in dotted zones) cyclone modification.*
Measurements filter ash: ■
Measurements cyclone ash: ◆

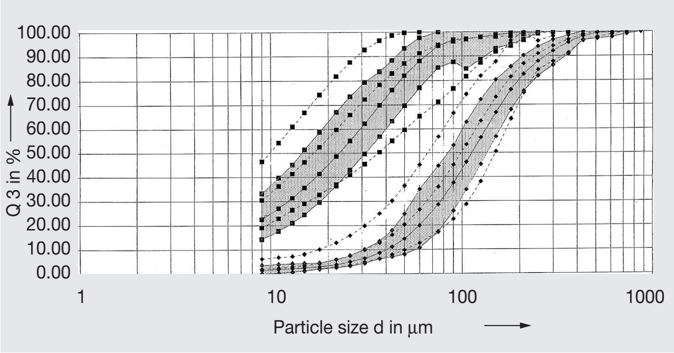

*Figure 8. Power plant EVO/Boiler DE 12/Filter- and Cyclone ash particle-size distribution curves before (dashed lines) and after (full lines in dotted zones) cyclone modification.*
Measurements filter ash: ■
Measurements cyclone ash: ◆

### Power Plant Berrenrath/Rheinbraun

Modifications:

Excentrical shift, narrowing and elongation of vortex finder.

*Results*

Addition of sand has been reduced by 60 % from 20 t/day to 8 t/day. Other measurements are not available.

*Conclusions*

The excentrical shift and narrowing of the vortex finder has led to a better cyclone separation efficiency which resulted in a strong increase of solids circulation rate and thus in economizing adding of sand.

### Power Plant Wachtberg/Rheinbraun

Modifications:

Vortex finder excentrically narrowed at its lower part and elongated.

*Results*

Addition of sand has been reduced from 10 to 15 t/day onto below 2 t/day. Other measurements are not available.

*Conclusions*

As for power plant Berrenrath.

### Power Plant Gardanne/Electricité de France

Modifications:

Vortex finder excentrically narrowed at its lower part and elongated.

*Results*

Pressure drop measurements in the upper part of the furnace show that the solids loading into the cyclones has been augmented from 15 to 20, i.e. the solids circulation rate has been increased by about 30 %. The particle size distribution of the circulating ash is finer than before modification: A shift of the mean particle size $d_{50}$ from 200 to 220 µm onto 175 µm has been measured. The heat transfer onto the heater surfaces thus improved considerably, but has still to be optimized by the same magnitude of order as achieved now. The operating behaviour of the boiler is more stable: The fluidized bed coolers are now operated by the optimal mass flow of ash, injection of water could be strongly reduced (for details see [3, 4]).

*Table 2. Cyclone improvements in 4 CFB power plants and its effects on their boiler performance.*
*Values marked with $^1$ are calculated, all others are measured.*
*The value marked with $^2$ corresponds to the measured reduction of the temperature in the upper part of the furnace.*

| Power plant | Gardanne | Goldenberg DE K | Goldenberg DE J | Wuppertal |
|---|---|---|---|---|
| Technical data | | | | |
| Steam generation t/h | 750 | 400 | 290 | 170 |
| Fuel | Local lignite | Brown coal | Brown coal | Hard coal |
| Number of cyclones | 4 | 4 | 4 | 2 |
| Cyclone diameter mm | 7400 | 5500 | 3710 | 4580 |
| Modifications | Insert excentr. narrowed at its lower edge and elongated | Insert excentr. narrowed at its lower edge and elongated; threshold in duct | Insert excentr. narrowed at its lower edge and shortened | Exzentrical boarding of insert (no shift of its axis) |
| Insert diameter mm | 3400 → 2900 | 2480 → 2100 | 2500 → 1950 | 1830 |
| Excentrical shift mm | 0 → 300 | 0 → 190 | 0 → 135 | 0 |
| Angel of excentr. shift ° | 210 | 225 | 260 | 0 |
| Insert length mm | 500 → 1100 | 1440 → 2040 | 3510 → 3000 | 1400 |
| Results | | | | |
| Loading of circulating ash | 15 → 20 | 5.1 → 7... 8$^1$ | 0.9 →1.2 ...1.4$^2$ | 5.4 → 5.4 |
| Adding of sand | already before modification = 0 | 800 - 1000 → 50 - 150 at 3 - 3.5 % ash content in coal<br>800 - 1000 → 0 above 3.9 % ash content in coal | 50 - 150 → 0 | no change |
| $d_{50}$ of circulating ash in µm | (200...220) → 175 | 210 → 160 ... 180$^1$ | 200 → 160 ... 180$^1$ | no change |
| Operating behaviour | Operating behaviour more stable, improved heat transfer, reduction of injection water | Operating behaviour more stable with strong reduction of sand addition | Operating behaviour more stable, control much simpler; temperature in upper part of furnace reduced from 830 to 780 °C, adding of sand economized | no change<br>(cf. conclusions in section “PP Wuppertaler Stadtwerke”) |

*Conclusions*

As for the plants Berrenrath and Wachtberg.

Furthermore: The loading of circulating ash has still to be increased, the particle size distribution has still to be refined.

To achieve this goal a modification of the entrance duct according to section 2 is necessary.

### Power Plant Goldenberg-
### Boiler DE K/RWE

Modifications:

Vortex finder excentrically narrowed at its lower part and elongated; threshold at the beginning of the duct.

*Results*

Operating behaviour of the boiler more stable than before modification. Adding of sand reduced by 80 to 90 % from 800 to 1000 t/month onto 50-150 t / month, at an ash content of 3 to 3.5 % in the coal. Above 3.9 % ash content in the coal adding of sand is no more needed.

*Conclusions*

As for the plants Berrenrath, Wachtberg, and Gardanne.

### Power Plant Goldenberg-
### Boiler DE J/RWE

Modifications:

Vortex finder excentrically narrowed at its lower part and shortened.

*Results*

Solids circulation rate strongly increased.

Temperature in the upper part of the furnace reduced by 50 ° from 830 °C to 780 °C, resulting especially in a better absorption of sulphur.

The boiler can now be operated in a much simpler way.

Adding of sand reduced from 50 to 150 t/month to 0 t/month. CO-emission limiting condition fulfilled, as before modification. The new particle size distribution of the cyclone ash has not been measured.

*Conclusions*

As for the plants Berrenrath, Wachtberg, Gardanne and Goldenberg DE K.

*Remark*

On modifying the cyclone care has to be taken not to increase the solids circulation rate too much. If the “cold” ash mass flow (about 400 °C), recirculated into the furnace, becomes too large, the bed temperature will be lowered onto a non-permissible value and the CO-emission will become too high. Therefore the required increase of separation efficiency value had to be obtained very accurately by designing the modifications.

### Power Plant of Wuppertaler Stadtwerke

Modifications:

Excentrical boarding of insert, but without excentrical shift of the insert axis. A complete shift or excentrical narrowing of the insert could not be performed due to time problems.

*Results*

No change of particle size distributions, no change of separation efficiency.

*Conclusions*

The inserts axes should be shifted as in the other plants.

## Effect of Cyclone Improvements on Solids Circulation Rate and Solids Particle Size Distribution

All relevant cyclone data before and after the cyclone modification are calculated on the basis of the cyclone theory described in [11]. This theory has been applied successfully for solid loadings of the entering jet below $\mu = 20$, which is usually the case in present commercial CFB boilers. For loadings far beyond this value *Hugi* (1997) found in a cold pilot plant some deficiencies between theory and measurement, concerning especially the pressure drop [8].

When calculating the cyclone efficiency in a CFB-boiler it is important to take into account not only the geometry of the cyclone, but also the geometry- and performance data of the other components of the facility, which are concerned with solids circulation: The diameter of the downcomer has to be large enough and the fans for the flue gas in the riser have to be strong enough to put through the augmented solids mass flow after a cyclone modification. Otherwise a strong increase of circulating ash mass flow rate will not be realized. The gas and solids velocity in the entrance zone of the cyclones are strongly influenced by the shape of the entrance duct. In addition the mass flow and the velocities of the solids are varying considerably over the height of the duct. Both facts are taken into account in computer programmes (see [2]).

For the plant manager it is neccessary to get at least quantitative estimations, what will be the effect of a cyclone modification on the boiler performance, i.e. at first on MFR and PSD of the circulating ash. Then process data like thermal and emission conditions after the modification can be estimated.

The results of cyclone improvements in several large industrial plants show clearly the strong influence of an increased separation efficiency on the ash inventory of the boiler (see Tables 1 and 2). However these data are not sufficient to deduce a general quantitative correlation between the cyclone separation efficiency on the one hand and MFR and PSD on the other hand.

The following simple consideration shows that on the basis of mass flow balances an approach to a quantitative understanding of this correlation is possible: Furnace, entrance duct, cyclone and ash removing system together constitute a circuit for the circulating solids. This circuit is fed from outside by inert material, i.e. unburnable solids like coal-ash and sand. Also inert material is extracted from the circuit, i.e. bed ash, cyclone- or fly-ash. The total input and the total output mass flow of inert material must be equal in a stationary state of the boiler. Otherwise the circuit would be emptied or plugged.

The consequences of this consideration will become clear in a simple example with the data:

| | |
|---|---|
| Coal input rate: | $\dot{M}_{coal} = 100$ t/h |
| Ash content of coal: 3 %,<br>therefore input rate<br>of coal-ash | $\dot{M}_{coal\text{-}ash} = 3$ t/h |
| Injection of inert material<br>like sand, flyash and<br>cyclone ash | $\dot{M}_{inj} = 0$ t/h |
| Extraction of bed ash | $\dot{M}_{bed} = 1$ t/h |
| Cyclone separation efficiency | $\eta = 99.4$ % |

Due to the balance of input and output mass flow the emission rate of the cyclone is

$$\dot{M}_{em} = \dot{M}_{coal\text{-}ash} + \dot{M}_{inj} - \dot{M}_{bed} = \\ = (3 + 0 - 1)\ \text{t/h} = 2\ \text{t/h} \qquad (2)$$

Then the solids circulation rate is

$$\dot{M}_{circ} = \frac{\dot{M}_{em}}{1 - \eta/100} = 333\ \text{t/h} \qquad (3)$$

If 0.5 t/h sand are added to the boiler, i.e. $\dot{M}_{inj} = 0.5$ t/h, and no other mass flow injection or extraction is changed, the emission rate increases according to (2) from 2 onto 2.5 t/h and the solids circulation rate then increases by 25 % onto the value

$$\dot{M}_{circ} = \frac{\dot{M}_{em}}{1 - \eta/100} = \frac{2.5\ \text{t/h}}{1 - 0.994} = 417\ \text{t/h} \qquad (4)$$

The same increase can be achieved if, instead of adding sand, the cyclone separation efficiency is increased from 99.40 to 99.52 %

$$\dot{M}_{circ} = \frac{\dot{M}_{em}}{1 - \eta/100} = \frac{2\ \text{t/h}}{1 - 0.9952} = 417\ \text{t/h} \qquad (5)$$

Thus, increasing the cyclone separation efficiency from 99.40 to 99.52 % has the same effect as adding 0.5 t/h or 350 t/month of sand!

The general mathematical model for calculating MFR takes into account all possible input- and output-mass-flows of the solids in the circuit like e.g. extraction of cyclone-ash or addition of lime. PSD is then calculated by balancing mass flows for every particle size d and using the fractional efficiency $\eta_F$ (d) of the cyclone instead of the total efficiency $\eta$ used for calculating MFR. The parametrization of fragmentation of the circulating solids is adapted to measured data before cyclone modification. $\eta_F(d)$ is calculated according to *E. Muschelknautz* et al [11] (for details see [12]).

## Conclusions

By small changes of the cyclone geometry the performances of seven CFB power plants have been improved considerably. The effect of cyclone modifications on MFR and PSD can be estimated on the basis of mass flow balances, of the cyclone theory according to *E. Muschelknautz et al* [11] and of the measured plant data before modification.

The results of this investigation clearly show that the separation efficiency of cyclones in CFB combustions has a crucial influence on the solids inventory in the boiler. Already improvements of the separation efficiency by less than a fraction of 1 % have a strong impact on the solids circulation rate and the refinement of its particle size distribution! Therefore the cyclone has to be designed very accurately to achieve the desired design parameters of the ash inventory in the boiler. The positive results of cyclone modifications in the big commercial CFB boilers make clear that probably a large potential resulting from an improvement of cyclones has not been used yet in many plants. If the cyclones can be improved there, the consequences are a sharply reduced addition of inert material (sand or ashes from silos), a distinctly better heat transfer, a stable operating behaviour of the boiler and further effects, mentioned in the introduction, which all contribute to considerable cost reductions.

## Nomenclature

| | | |
|---|---|---|
| $\Delta b$ | m | Widening of entering gas flow in cyclone entrance zone |
| c | m/s | Solids velocity |
| $c_e$ | m/s | Solids velocity at the end of the duct |
| d | μm | Particle size |
| $d_{50}$ | μm | Mean particle size |
| $d_{min}$ | μm | Minimum particle size |
| $d_{max}$ | μm | Maximum particle size |
| $d_S^*$ | μm | Cut size for cyclone |
| D | m | Typical duct width (for calculating Froude number) |
| e | m | Excentrical shift |
| F* | - | Froude number |
| g | $m/s^2$ | Acceleration due to gravity |
| k | - | Exponent for calculating drag |
| l | m | Lengthwise coordinate, equal to 0 at entrance to constricted duct immediately upstream of cyclone |
| L | – | Dimensionless lengthwise coordinate, equal to 0 at entrance to constricted duct immediately upstream of cyclone |
| dl | m | Infinitesimal lenght along duct |
| $\dot{M}_{bed}$ | t/h | Extration rate of bed ash |
| $\dot{M}_{circ}$ | t/h | Solids circulation rate |
| $\dot{M}_{coal}$ | t/h | Rate of coal addition |
| $\dot{M}_{coal\text{-}ash}$ | t/h | Injection rate of coal-ash, fed into the furnace with coal |
| $\dot{M}_{cyc}$ | t/h | Extration rate of cyclone ash |
| $\dot{M}_{em}$ | t/h | Emissions rate |
| $\dot{M}_{gas}$ | t/h | Gas mass flow |
| $\dot{M}_{inj}$ | t/h | Addition rate of inert material like sand, flyash or cyclone ash from silos (excluding coal-ash) |
| $\dot{M}_S$ | t/h | Solids mass flow |
| p | Pa | Pressure |
| $\Delta p_{cycl.}$ | Pa | Pressure drop of cyclone |
| $\Delta p_E$ | Pa | Pressure drop in the entrance duct |
| Q3(d) | % | Cumulative undersize |
| $Re_S$ | - | Reynolds number of solids |
| t | °C | Temperature |
| $u_a$ | m/s | Tangential velocity at cyclone radius |
| $u_i$ | m/s | Tangential velocity at insert radius |
| $\bar{u}$ | m/s | Mean tangential velocity = $= \sqrt{u_a \cdot u_i}$ |
| $\nu$ | m/s | Gas velocity |
| $\nu_e$ | m/s | Gas velocity at the end of the duct |
| $\nu_{duct}$ | m/s | Gas velocity at the beginning of the duct |
| $\dot{V}$ | $m^3/s$ | Gas flow rate |
| $w_S$ | m/s | Settling velocity of a particle cloud |
| $\varphi$ | ° | Angle of excentrical shift |
| $\eta$ | % | Cyclone separation efficiency |
| $\eta_{gas}$ | Pa · s | Gas viscosity |
| $\mu$ | - | Solids loading |
| $\rho_{Gas}$ | $kg/m^3$ | Gas density |

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