EFFECT OF PRIMARY AIR MALDISTRIBUTION DUE TO NOZZLE WEAR ON CFBC PERFORMANCE

Martin Weng[1], Adlan Omer[1]

[1] *aixprocess GmbH, Alfonsstrasse 44, 52070 Aachen, Germany*

ABSTRACT

As in any fluidized bed application, the nozzle grid of a CFBC riser has the task of supplying fluidization / primary combustion air to the combustion chamber with a uniform distribution and at the same time retaining the coarse ash to form a dense bed at the riser bottom. A typical issue in large scale CFB's is a maldistribution of primary air caused by either excessive nozzle wear in certain grid regions or clogging and blocking on the other hand.

The contribution presents a joint method of grid nozzle measurement and CFB combustion simulation for plant performance assessment. Results of erosion patterns and their effect on primary air maldistribution and subsequent combustion issues are shown for a 105MW_{th} CFBC are shown.

The method of nozzle grid field measurements combined with detailed flow and combustion computations provides the CFBC operator with information on required number of nozzles to be changed in order to ensure uniform air distribution and at the nozzle grid. As a prerequisite for burn-out quality, boiler efficiency and emission control, the nozzle grid assessment is an effective measure to reduce boiler maintenance costs.

NOZZLE MEASUREMENTS

A good condition of the air nozzle in the nozzle floor is a prerequisite for even air distribution and thus an optimal fluidisation of the bed. The distribution of bed material and fuel are depending on good air distribution, as well as the internal circulation of ash in the combustion chamber and thus the influence on emission values and burn-out is significant. The main parts are the pipe with holes on the top, and a casted nozzle head, prevent the backflow from ash into the air box.

A typical primary air nozzle is shown in Fig. 1.

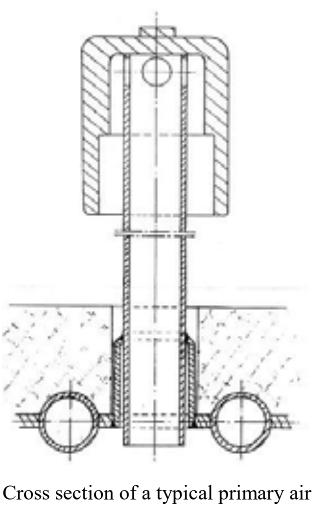

Fig. 1. Cross section of a typical primary air nozzle

Air nozzles in a CFB systems are subject to a continuous wear, due to continuous ash movement and high temperatures. The nozzles can be controlled from the outside to wear only the nozzle head (Fig. 2) and the tube. The inner wear on the holes could be observed visually only by means of an endoscope. This test method is however very expensive and provides no quantifiable statement about the state of wear.

Fig. 2. Damaged Primary Air Nozzle due to External Wear

To measure the internal wear the individual pressure drop may serve as in indicator. Therefore a device was developed to measure the internal pressure drop. It is composed of an air blower (electric fan), a hose, an adapter and a pressure gauge. The components of the measuring device can be seen in Figure 3.

Fig. 3. Device for the Measurement of internal Pressure Drop of individual Primary Air Nozzles

Prior to the actual measurement, a calibration measurement is carried out. This calibration is a measurement of a new nozzle allowing a comparison to the new condition. The actual measurement of the air nozzles is conducted from the air box beneath the nozzle floor through the tubes. The adapter is pressed against each individual nozzle tube, a quantified amount of air is blown through and the difference of the static pressure in the nozzle and the atmospheric pressure is measured and documented for each nozzle. The internal diameter of the adapter should be similar to the diameter of the nozzle tube to obtain a measurement error as low as possible. For this, a specific adapter is used for each nozzle design.

Experience shows good and reliable accuracy. The measured values for the calibration (new) nozzle can be reproduced with an error of ±0. 5 mbar. The accuracy for measurements of nozzles in nozzle floor is about ±1 mbar. Since the actual pressure drops for the nozzles are typically in the range of 25-30 mbar the error is acceptable.

The time required for the carrying out the measurements is relatively low. A single nozzle can be checked in about 15 seconds. Considering the preparation time a complete nozzle floor with approx. 500 nozzles is measured in about 4 hours.

The measured values are entered in tables (Fig. 4, left). In addition to the values in the tables a colour mapping of the measured value to the corresponding nozzle (Fig. 4, right) is made to allow an easy overview about the actual state of the nozzle floor. This gives the opportunity to identify regions with blockings or high erosion and also and easy comparison to measurements conducted in the past. This helps to recognize erosion patterns and changes over longer operation times.

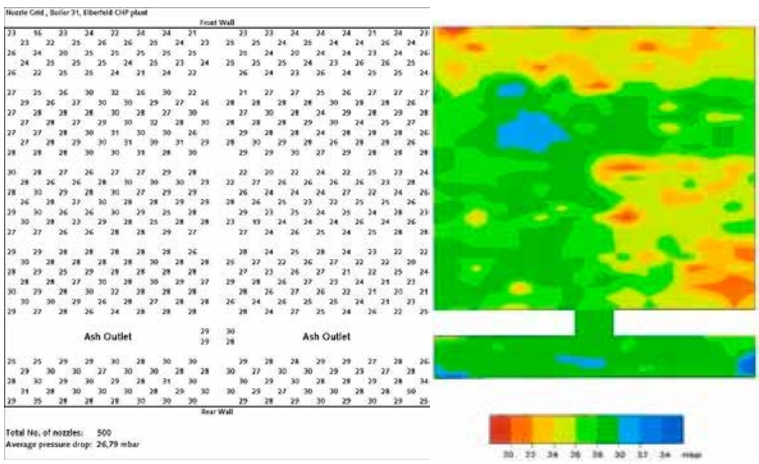

Fig. 4. Documentation of Measured Values

A low value means that the nozzle is heavily worn, and if the pressure drop is below a predetermined threshold value the nozzle has to be replaced. Of course nozzles also have be replaced, when showing strong wear at the nozzle head. A high pressure drop means that the nozzle is clogged by ash and has to be cleaned or replaced.

With the measurement results the plant operators receive a very good overview about the condition of the nozzle floor and additionally detailed information about the individual nozzle, resulting in a task schedule during turn-over.

However, these results also serve as excellent boundary conditions for numerical simulations. Either to understand how the CFBC performs under current conditions or to in reverse to enable modifications on Oxygen distribution, which are tested in CFC, through modifications of the air distribution in the nozzle floor.

NUMERICAL SIMULATION IN FLUIDISED BEDS AND DENSE PARTICLE FLOWS

The CFD simulations make use of the Multiphase Particle-in-Cell (MP-PIC) method (O'Rourke et al., 2001). The CPFD method solves the fluid and particle momentum equations in three dimensions. The fluid is described by the Navier-Stokes equation in bi-directional coupling with the discrete particles. The MP-PIC numerical scheme is a Lagrangian description of particle motion described by ordinary differential equations with back-coupling to the fluid. This

Computational Particle Fluid Dynamics (CPFD) solution as applied in the commercially available software Barracuda VR® is aimed at solving industrial problems, which are generally physically large systems. In the CPFD scheme, a numerical particle is defined where particles are grouped with the same properties (species, size, density, etc.). The numerical particle is an approximation similar to the numerical finite control volume where a spatial region has a single fluid property. Using numerical particles, large commercial systems containing billions of particles can be analyzed using only millions of numerical particles. The simulation is strictly transient, thus accounting for the inherently fluctuating character of flows with high solid volume fractions.

The volume average two-phase continuity equation for the fluid (here written without interphase mass transfer) is

$$\frac{\partial \theta_f \rho_f}{\partial t} + \nabla \cdot \left(\theta_f \rho_f u_f\right) = 0 \tag{1}$$

with fluid velocity u_f and fluid volume fraction θ_f. The volume average two-phase incompressible momentum equation for the fluid is

$$\frac{\partial \theta_f u_f}{\partial t} + \nabla \cdot \left(\theta_f u_f u_f\right) = -\frac{1}{\rho_f}\nabla p - \frac{1}{\rho_f}F + \theta_f g + \frac{1}{\rho_f}\nabla \cdot \tau \tag{2}$$

where ρ_f is fluid density, p fluid pressure, τ the macroscopic fluid stress tensor, and g the gravitational acceleration. F is the rate of momentum exchange per volume between the fluid and particles phases.

The particle acceleration is

$$\frac{d\,u}{dt} = D_p\left(u_f - u_p\right) - \frac{1}{\rho_p}\nabla p + g - \frac{1}{\theta_p \rho_p}\nabla \cdot \tau_p \tag{3}$$

where u_p the particle velocity, ρ_p particle density and τ_p particle normal stress. The terms represent acceleration due to drag, pressure gradient, gravity and inter-particle normal stress gradient. Particle properties are mapped to and from the Eulerian grid. The interpolation operator is the product of interpolation operators in the three orthogonal directions.

The interphase drag coefficient is

$$D_p = C_d \frac{3}{8}\frac{\rho_f}{\rho_p}\frac{|u_f - u_p|}{r} \tag{4}$$

where μ_f is the fluid viscosity, r is the particle radius and C_d, and the drag correlation from Wen and Yu, 1996.

Particle-to-particle collisions are modelled by a particle normal stress expression. The particle stress is derived from the particle volume fraction which is in turn calculated from particle volume mapped to the grid. The particle normal stress model used here is

$$\tau = \frac{P_s \theta_p^{\beta}}{max[(\theta_{CP} - \theta_p), \epsilon(1 - \theta_p)]} \tag{5}$$

where P_s is a material parameter, β a model parameter in the recommended range of $2 \leqslant \beta \leqslant 5$ (Auzerais et al., 1988), θ_{CP} is particle close pack volume fraction and ε is a small number of the order of 10^{-7} to remove the singularity. The close-pack limit is somewhat arbitrary and depends on size, shape and ordering of the particles. Therefore the solution method allows the particle volume fraction, at times, to slightly exceed close-pack which is physically possible considering that shifting or rearranging of granular materials may occur. The particle normal stress is mapped to discrete particles. Because particles have sub-grid (no grid) behavior, the application of the normal stress gradient to a discrete particle accounts for the particle properties and whether the particle is moving with or against the stress gradient.

The gas phase turbulence is taken into account by a Large Eddy model with a Smagorinsky model based on a coarse sub-grid allowing for time steps in a millisecond order of magnitude. However, there are currently no validated turbulence models for dense particle flow. Large density and size particles act as large eddies of momentum transfer while gas flow around close pack particles produces small sub-grid eddies and dissipation (Snider, 2001).

CFD RESULTS OF THE FLUIDIZED BED COMBUSTOR IN WUPPERTAL (GERMANY)

In the power plant in Wuppertal Elberfeld, Germany tube damage in a locally restricted area of the furnace roof was observed. One root cause assumption for the wear was a partly worn distributor grid releasing a massive primary air streak into the furnace. To proof this assumption a combination of nozzle measurements and detailed CFD analysis was conducted. The results of the nozzles measurements shall be used as verified boundary conditions for the CFD simulation.

The Wuppertal Elberfeld plant consists of 2x137 MWth CFB boilers manufactured by L+C Steinmüller and was commissioned in 1991. Actual data is given in table 2. The operational modes depend on the district steam and heat demand for industrial and communal use and the market price for electricity. Due to the German power market regulations for renewable energies, the plant undergoes daily load alternations between 60 – 100% load with an typical ratio of partial to full load of 3:1. The specific requirement is a high plant flexibility and fast load change velocities.

Table 1: Elberfeld CFB plant data

Firing	Atmospheric Circulating Fluidized Bed (system LURGI)
Steam generator	Once Through (system Benson)
Fuel	Hard coal, Residuals Derived Fuel (RDF) up to 25% thermal input after retro-fit
Thermal output	2 x 137 MW
Steam parameters	HP 2 x 47,2 kg/s, 535°C, 201 bar LP 2 x 42,8 kg/s, 535°C, 46 bar
Feed water temperature	260°C
Operation hours - XII/2013	149,108 (B31), 139,824 (B32), ~ 80% full load
Annual op. hours	~ 4,500 – 7,000

In Figure 5 the Wuppertal Elberfeld plant is depicted.

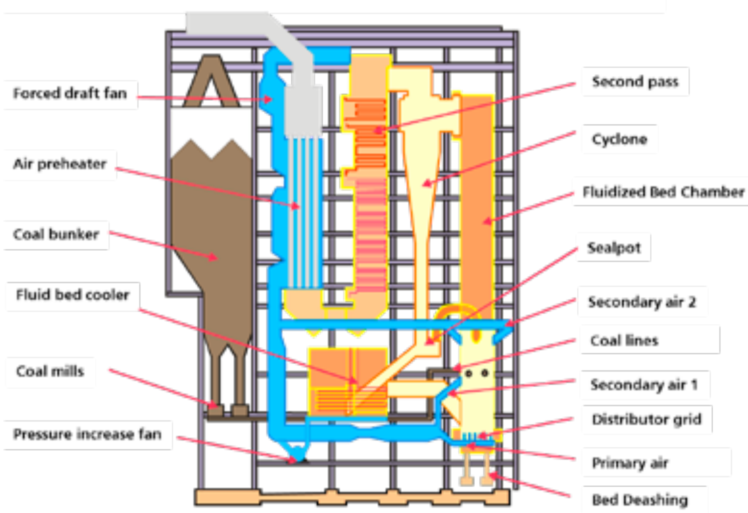

Fig. 5. Wuppertal Elberfeld CFB Plant

As mentioned above the main motivation for a comprehensive process analysis of the Elberfeld CFB was a tube damage causing an unplanned shut-down, revealing a very specific wear pattern under the boiler roof in direct line above the RDF fuel inlet located in the bottom left corner (Fig. 6). The deformations suggest the impact of large particles being shot against the roof with high velocities.

Fig. 6. Wuppertal Elberfeld plant: Specific Tube Damages at the Roof

The damages occurred after a series of former operational trials with changing the bed height from normal operation characterized by dp = 175 mbar throughout the fluidized bed chamber ("high bed") to dp = 150 mbar ("low bed"). In another trial, the secondary air distribution had been adopted from the original case "S1" to a nearly equalized distribution "S2". The operational trials were superimposed by daily load changes with eventual overload operations of 102%. As a superposition of a set of operational conditions, the main cause for the tube damages could not be easily identified from operational observations.

Although the fluidization is highly turbulent, it is well known that lateral dispersion in large scale fluidized beds is not sufficient for complete mixing of any maldistribution or streak. Figure 4 shows the result of the nozzle grid measurement for the Elberfeld plant. There is a region of high nozzle pressure drop along the front wall indicating some partial blocking, but no noticeable wear (as indicated by low nozzle pressure drop) in the section of RDF inlet. Generally the measurements show a pressure drop with a rather uniform distribution and a central orientation across the distributor grid.

For further analysis, CFD simulations were performed for the operation conditions (bed height, secondary air distribution, boiler load). Fig. 7 shows instantaneous values for particle speed (left) and flue gas speed (right). Single particles are accelerated well above 10 m/s by the local flue gas fluctuations, enabling big particles to be transported throughout the fluidized bed chamber.

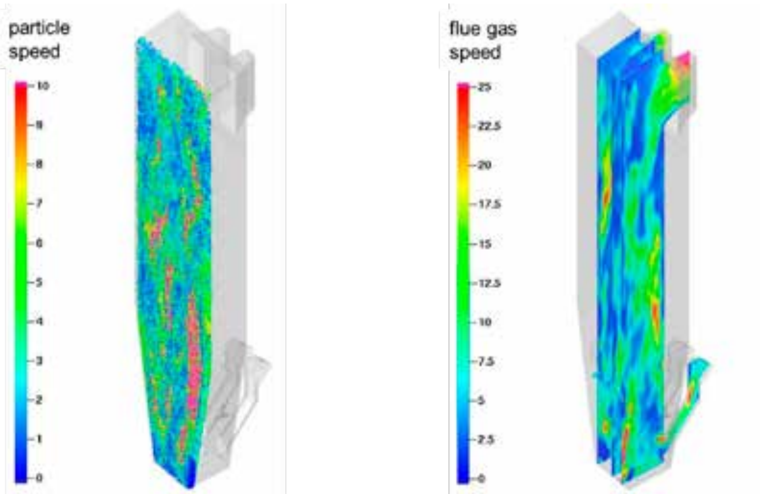

Fig. 7. Instantaneous values of particle speed (left, max value 10 m/s)
and flue gas speed (right, max value 25 m/s)

The wear evaluation (Fig. 8) is based on time- and area-related particle impacts and shows the qualitative trend of different scenarios.

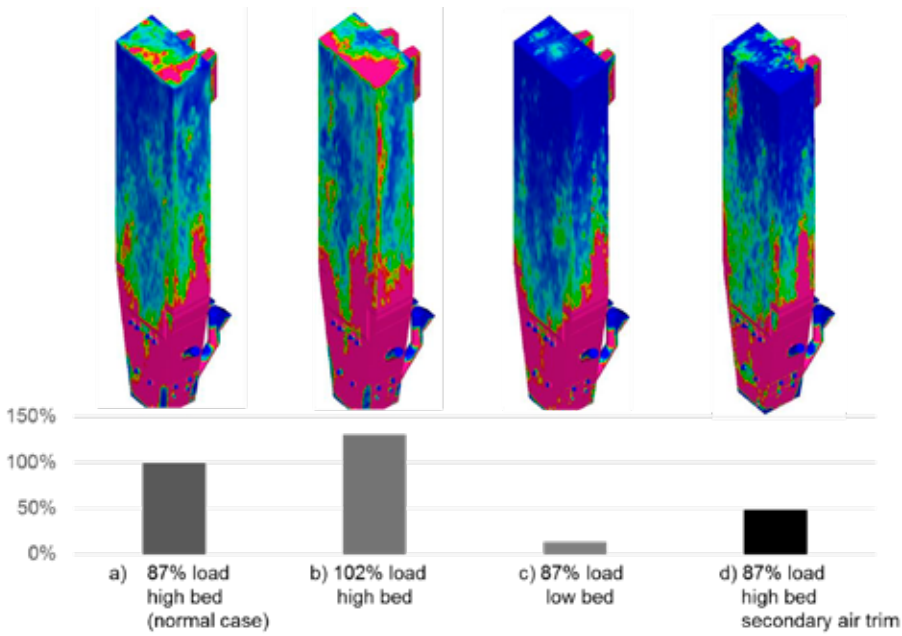

Fig. 8. Wear scenario simulations: plot of wall/roof wear
intensity and normalized values for roof wear

The normal case (a) reveals the wear spot in the upper right edge as observed from the real plant. The wear is further increased by an enhanced load (b), whereas a simple lowering of the bed height reduces the wear significantly (c). A similar tendency but with lower efficiency can be achieved by secondary air trimming (d). The secondary air trimming is limited by the high requirement of oxygen above the asymmetric secondary fuel inlet in order to burn out the high amount of volatiles released by RDF.

As a result of the study, the bed inventory was slightly reduced and the number of maximum load events was reduced. Also the nozzles in the nozzle floor are measured regularly to avoid unobserved wear, which again lead to locally high air velocities, dragging large particles to the roof. In the meantime, no more specific roof damages could be observed.

REFERENCES

Andrews, M.J., O'Rourke, P.J.: The Multiphase Particle-In-Cell (MP-PIC) Method for Dense Particle Flow. Int. J. Multiphase Flow 22, 379–402, 1996

Auzerais, F.M., Jackson, R., Russel, W.B.: Journal of Fluid Mechanics 195 (1988)

Snider, D. M.: An Incompressible three dimensional multiphase particle-in-cell model for dense particle flows. Journal of Computational Physics 170, 523-549, 2001

Wen, C.Y. Yu, Y.H.: Chem. Eng. Progr.Symp., Ser. 62, 100-110, 1996

Weng, M., Nies, M., Plackmeyer, J.: Computer-aided optimisation of gas-particle flow and combustion at the Duisburg circulating fluidised bed furnace, VGB PowerTech 8|2011