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Experimental and numerical investigation of particle erosion caused by pulverised fuel in channels and pipework of coal-fired power plant

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Abstract

A small test facility for investigation of particle-wall impact, specially designed for use of pulverised fuel, will be presented. By means of it the bouncing parameters, coefficients of restitution and friction, of coal powder onto a steel wall and the erosion effects have been measured. Based on this experimental data a numerical simulation of transport of pulverised fuel in a complex splitting device, a so-called bifurcator with riffle box, has been carried out. The numerical approach together with the simulation results will be presented for this application to numerical erosion prediction for devices of coal-fired power plants.

1. Introduction

In power plants using large utility coal-fired boilers for generation of electricity the coal is pulverised in coal mills and then it has to be pneumatically transported and distributed to a larger number of burners (e.g. 30 to 40) circumferentially arranged in several rows around the burning chamber of the boiler. Besides the large pipework flow splitting devices are necessary for distribution of an equal amount of pulverised fuel (PF) to each of the burners. So called trifurcators (without inner fittings or guiding vanes) and "Riffle" type bifurcators are commonly used to split the gas-coal particle flow into two or three pipes or channels with an equal amount of PF mass flow rate in each outflow cross section of the flow splitting device.

These PF flow splitting devices are subject of a number of problems. First of all a poor distribution of PF over the burners of a large utility boiler leads to operational and maintenance problems, increased level of unburned carbon and higher rates of NO_X emissions. Otherwise the bended pipework leading from the coal mills to the flow splitters and further to the burners results in an unequal concentration distribution over the cross section of the pipes (particle roping). This causes maldistribution of fuel between burners in the flow splitter and further leads to plant maintenance problems due to an uneven wear of PF pipework as well as the flow splitters themselves.

In order to understand the behaviour of PF in pipework the knowledge of particle-wall physics is required. The most recent models of the particle-wall impact use constant values of the collision coefficients ***k*** and ***f*** for a given particle-wall combination. The complex connection between particle, wall and flow conditions before impact leads to a big number of partly inconsistent results [Brauer (1980), Illyes (1986); Tabakoff (1987), Govan (1989)]. In this paper investigations of the particle-wall collision process with irregular shaped PF were carried out.

Secondly erosion rates were obtained as a function of particle impact angle and velocity for the material combination of PF and pulverised fuel ash (PFA) with a steel target. The erosion rate depends on the energy exchange between the erodent particle and the impacted material surface which can be characterised by restitution coefficients. However it was already found by Grant et al. (1975) that the restitution ratio v_2/v_1 does not give sufficient information with regard to erosion. Therefor the restitution ratio was broken down into a normal velocity restitution ratio v_{N2}/v_{N1} and a tangential velocity restitution ratio v_{T2}/v_{T1}. The results show that the normal component of velocity does not contribute significantly to ductile erosion. As a result of the experimental investigations the erosion rate has been expressed in terms of the restitution parameters. These data give the foundation for the numerical prediction of particle erosion in devices of complex geometry like e.g. in the investigated "Riffle" type bifurcators.

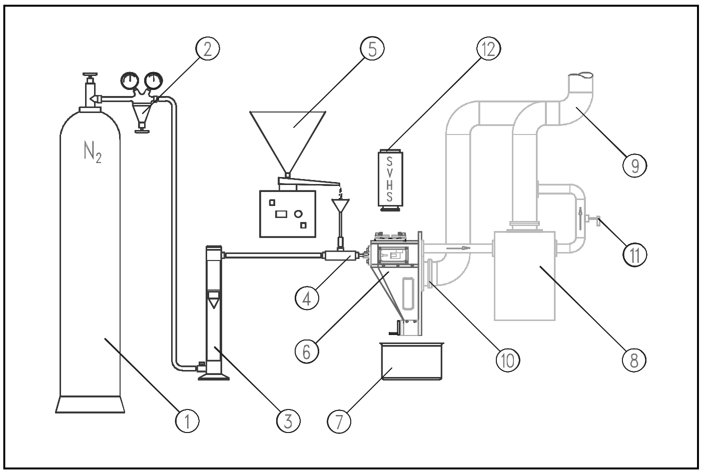
Nomenclature

C_D, C_A	drag and lift coefficients
d_P, r_P	particle diameter and radius
G	gravitational acceleration
k, f	coefficients of restitution and kinetic friction
$\dot{N}_P$	particle number flow rate
Re, Re_P	Reynolds and particle Reynolds number
u, v, w	velocity in x-, y- and z-direction
v_{rel}	absolute value of particle-fluid relative velocity
v_N, v_T	normal and tangential velocity component
Ω	fluid rotation
υ	kinematic viscosity
ρ	density
ω_P	particle rotational velocity
ω_{rel}	absolute value of particle-fluid relative rotational velocity

Subscripts

F	fluid
P	particle
1	before impact
2	after impact

2. Test facility and measuring system



Legend:
1 gas cylinder (nitrogen)
2 reducing valve
3 flowmeter (rotameter)
4 injector
5 vibratory feeder
6 chamber with target
7 reservoir
8 filter
9 outlet for flue and pressure relieve
10 trap of pressure relieve with membrane
11 O_2-sensor
12 video camera

Fig. 1 Test facility

The tests of particle-wall interaction were performed in a chamber, manufactured out of bronze, with injector to accelerate the particles, a bouncing target and outlets for gas and particles. The particles were feeded by a vibrating chute into the injector. Its inside diameter was 3 mm. In order to accelerate the particles nitrogen, an inert gas, was used to avoid dust explosions. The particle velocity was 5 m/s to 30 m/s. Inside the chamber the rotatable target (made from steel St 38, 3mm * 20 mm, 35 mm thick) was adjusted to the intended impact angle. The point of particle impact was located 5 mm away from injector outlet. The particle velocities, that of bouncing and that of rebounced particles, were measured by two fibreoptical velocity probes as described by Petrak (1995). By moving the last-mentioned velocity probe on a circular arc through the rebounced jet the angle distribution of particle rate and velocity of rebounced particles was measured. The complete test facility is shown in Fig. 1.

From measured probability distribution of particle rate and particle velocity in rebounded jet the angle of rebound α_2, that is the angle of maximum particle rate, and velocity of rebound v_2 at this angle was obtained. By means of normal (subscript N) and tangential (subscript T) components of velocities of impact (subscript 1) and of rebound (subscript 2) the bouncing parameters, the restitution coefficient k and friction coefficient f, were calculated according to Sawatzki (1961):

$$V_{N2} = -k \; V_{N1} \tag{1}$$

$$V_{T\,2} = V_{T\,1} + \varepsilon \;\; (1+k)\, f V_{N1} \tag{2}$$

for sliding conditions and

$$V_{T2} = V_{T1} - \frac{2}{7}\left(V_{T1} + r\,\omega_1\right) \tag{3}$$

for non sliding particle-wall collisions. In the last case, what happens at high impact angles, angle and velocity of rebound are independent of the friction coefficient. More detailed formulae are in Frank et al. (1993) and Schade et al. (1998).

The Erosion tests were carried out in the same chamber. However the particle transport of very small particles from mean diameters of 45 µm to the gas-particle injector was impossible with the described vibrating chute. Therefore we designed a new particle feeding system for the fine coal powder. The PF was stored in a container with a porous bottom and the inert gas flow was divided in two parts . The first part flows trough the bottom of the PF container and generates a fluidised coal-gas bed. The particle –gas injector was mounted on the top of the particle container and sucks the fluidised coal by the help of the second gas flow in the transport tube. With this construction a sufficient disagglomeration of the coal powder was possible . A built in fibreoptical probe measures the particle velocity before impact.

As targets small steel plates of 40 * 10 * 3 mm^3 (mass 8.9 g) were used. Again several impact angles and impact velocities were investigated. The effect of erosion was weighted out with scales of Sartorius as well as the deformation of surface was measured with an "Rank Taylor Hobson" profilometer.

3. Experimental results for impact of pulverised fuel on a wall

The following figures show the results of the determination of the impact coefficients for the impact of coal onto a steel target. The coal particles under investigation had a diameter from 150 to 300 µm. Fig. 2 shows the measured coefficients of restitution in dependence on impact velocity V_1 and the impact angle a_1.

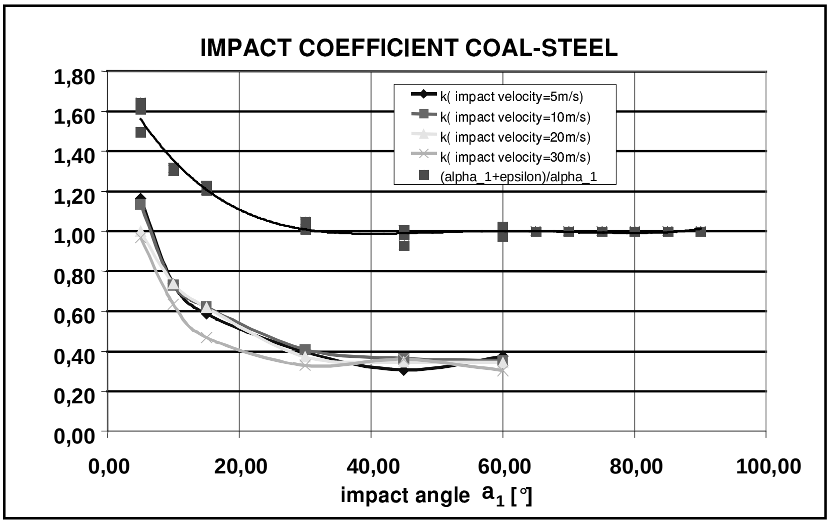


Fig. 2 Coefficient of restitution k and impact angle increase (see eq. (4))

All curves show a nearly constant value of $k = 0.36$ for impact angles $a_1 > 35$ °. With decreasing impact angles increases the restitution coefficients up to values higher than $k = 1$ at impact angle $a_1 = 5°$. The reason is the roughness of the wall and the irregular shape of the particles. In case of randomly distributed inclinations of a rough wall a particle hits with decreasing impact angle more and more inclinations against its trajectory. This results in a higher reflection angle compared with the impact onto a smooth wall (see Schade 1998). In addition, the irregular shape of the particles might lead to a higher reflection angle too and causes therefore restitution coefficients higher than $k = 1$.

With the assumption of a constant coefficient of restitution $k_{const} = 0.36$ and the measured values of V_{N1}, V_{N2}, a_1 and a_2 one can calculate the increased impact angle $b = a_1 + e$ seen by the impacting particle.

There is:

$$\tan\varepsilon = \frac{K * \sin\alpha_2 - \sin\alpha_1}{K * \cos\alpha_2 + \cos\alpha_1} \quad \text{with} \quad K = \frac{\frac{V_{N2}}{V_{N1}}}{k_{const}} * \frac{\sin\alpha_1}{\sin\alpha_2} \tag{4}$$

The corresponding value of $(\alpha_1+\varepsilon)/\alpha_1$ is also represented in Fig. 2. The values for all impact velocities and impact angles show the same tendency and can be fitted with only one graph.

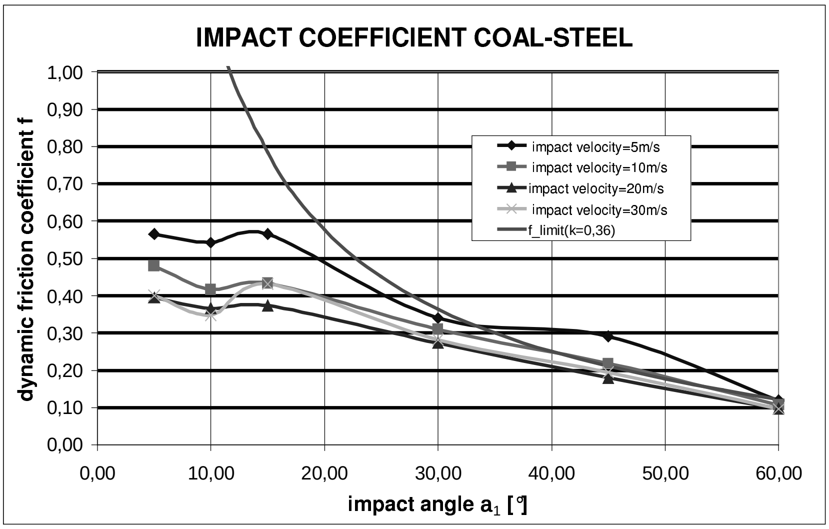


Fig. 3 Dynamic friction coefficient f

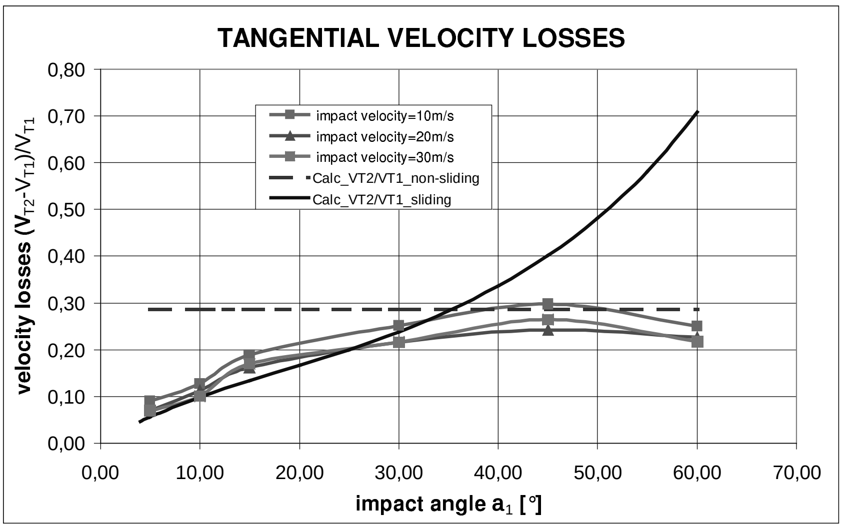


Fig. 4 Tangential velocity losses $(V_{T2}-V_{T1})/V_{T1}$

Fig. 3 shows the dynamic friction coefficient f for the same measurements in dependence of impact velocity and – angle too. The measurements are plotted together with the limit value of the dynamic friction coefficient f_l. The limit value f_l marks the border between sliding and non-sliding conditions and is calculated from

$$f_l = \frac{2}{7}\frac{\left|V_{T1} + r\,\omega_1\right|}{(1+k)V_{N1}}$$

with the obtained value k = 0.36 for the constant k-range in Fig. 2 and the assumption, that the rotational velocity ω_1 before impact is $\omega_1 = 0$.

The measurement plots for the dynamic friction coefficient follow at $a_1 > 35°$ the limit value f_l , that means in the range between 30° and 40° changes the particle-wall impact from sliding to sticking impact. For a better determination of the point of change between sliding and non-sliding impact Fig. 4 shows the losses of tangential velocity $(V_{T1}-V_{T2})/V_{T1}$ together with the calculated velocity loss for the sticking and the sliding impact. The experimental curves show an increasing value with increasing impact angle up to $a_1 = 35°$ and reach than the nearly constant value for the sticking impact. The last was calculated with $k = 0.36$. In order to fit the experimental values of the sliding impact with the calculated loss of tangential velocity (see Fig. 4, blue line) the sliding coefficient f_{const} was chosen to $f_{const} = 0.3$ and the fit was done with the increased impact angle ε (eq. (4) and Fig. 2) for small impact angles. The angle of the transition between sliding and sticking impact comes out to 35°.

In conclusion the investigated coal-steel impact is marked by the following parameter set:

- a constant coefficient of restitution $k = 0.36$
- a constant dynamic friction coefficient $f = 0.3$
- a border angle for transition from sliding to sticking impact $a_{1border} = 35°$
- and a roughness and shape induced impact angle increase $b / a_1 = b_{rel}$ with

$$b_{rel} = 9.522 \cdot 10^{-8} a_1^4 - 2.202 \cdot 10^{-5} a_1^3 + 1.837 \cdot 10^{-3} a_1^2 - 6.519 \cdot 10^{-2} a_1 + 1.816$$

4. The 3-dimensional Eulerian-Lagrangian approach

Experimental results from investigations of particle-wall interaction (parameters of particle-wall bouncing model and experimentally predicted particle erosion rates) have been implemented into an Eulerian-Lagrangian model for numerical prediction of gas-particle flows in e.g. pipework and flow splitting devices of coal-fired power plants. Besides the prediction of the mass flow rate splitting ratio of PF in the splitting devices in front of the different rows of PF burners of an industrial boiler one primary goal of these flow simulations was also the numerical prediction of particle erosion to the pipework and guiding vanes of the flow splitting devices (tri- and bifurcators).

For these numerical simulations a 3-dimensional Eulerian-Lagrangian approach developed by Frank et al. (1992, 1997 and 2000a) was used. The 3-dimensional two-phase (gas-particle) flow in the PF flow bifurcator is described by assuming that the particulate phase is dilute and that the particle loading is rather low. This assumption satisfies the neglect of inter-particle effects and contributing source terms in the Navier-Stokes equations due to particle-fluid interaction. Further the two-phase flow is assumed statistically steady, incompressible and isothermal. Then the motion of the fluid phase can be described using the time-averaged form of the Navier-Stokes equations. For consideration of fluid turbulence a standard k-ε turbulence model was used in the present numerical simulations.

The disperse phase is treated by the application of the Lagrangian approach. Each calculated particle represents a large number of physical particles of the same physical properties which is characterised by the particle flow rate $\dot{N}_P$ along each calculated particle trajectory. The prediction of the particle trajectories is carried out by solving the ordinary differential equations for the particle location and velocities. Assuming that the ratio of fluid to particle density is small ($\rho_F / \rho_P \ll 1$) these equations read :

$$\frac{d}{dt}\begin{bmatrix} x_P \\ y_P \\ z_P \end{bmatrix} = \begin{bmatrix} u_P \\ v_P \\ w_P \end{bmatrix} \tag{5}$$

$$\frac{d}{dt}\begin{bmatrix} u_P \\ v_P \\ w_P \end{bmatrix} = \frac{3}{4}\frac{\rho_F}{\left(\rho_P + \frac{1}{2}\rho_F\right) d_P}\left(v_{rel}\, C_D \begin{bmatrix} u_F - u_P \\ v_F - v_P \\ w_F - w_P \end{bmatrix} \right.$$

$$\left. + \frac{2\nu_F^{1/2}}{\pi |\vec{W}|^{1/2}} C_A \begin{bmatrix} (v_F - v_P)W_Z - (w_F - w_P)W_Y \\ (w_F - w_P)W_X - (u_F - u_P)W_Z \\ (u_F - u_P)W_Y - (v_F - v_P)W_X \end{bmatrix} \right) + \frac{\rho_P - \rho_F}{\rho_P + \frac{1}{2}\rho_F}\begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix} \tag{6}$$

with

$$\vec{W} = \text{rot}\,\vec{v}_F\,, \qquad Re_P = \frac{d_P\, v_{rel}}{\nu_F}$$

$$v_{rel} = \sqrt{(u_F - u_P)^2 + (v_F - v_P)^2 + (w_F - w_P)^2}$$

These equations of motion of the disperse phase include at the right hand side the drag force, the lift force due to shear in the fluid flow field (Saffman force), the gravitational and added mass force. For the present numerical investigation the Magnus force due to particle rotation is neglected because of their minor importance for the very fine particles of the PF and PFA particle material. For larger and more inert particles the Magnus force has to be included at the right hand side of equation (6) as shown in Frank (2000a).

The values for the coefficients C_D and C_A can be found in literature Frank (1997), Sommerfeld (1996). Additionally for the lift coefficient C_A the correction obtained by Mei (Sommerfeld 1996) is taken into account. The effect of fluid turbulence on the motion of the disperse phase, which is regarded to be very important for the particle diameter range under investigation, is modelled by the Lagrangian Stochastic-Deterministic (LSD) turbulence model proposed by Schönung and Milojević (Frank 1992). The particle-wall collisions are treated according to the irregular bouncing model by Sommerfeld (1996) in the modified wall roughness formulation given in Frank (1997). For the coefficients of restitution k_W and dynamic friction f_W experimentally determined functions of particle incident angle has been used.

For the numerical prediction of particle erosion a number of different erosion models has been implemented. Therefor an experimentally predicted erosion intensity function has to be given for each combination of particle and wall material under investigation:

$$E = E\left(\alpha_1, V_{P1}, k_W, f_W, T, \ldots\right)$$

The erosion intensity is described as a function of the particle incidence angle and velocity, coefficients of restitution and dynamic friction, temperature and possibly other influencing parameters. A typical particle erosion model can be found e.g. in Tabakoff (1988) for fly ash particles ($d_P = 5\mu m$) on stainless steel with:

$$E = 8.19 \times 0.00377 \times F(T) \left[\left(\frac{V_1}{100} \right)^{2.19} \cos^2 a_1 \left(1 - e_T^2\right) \right.$$
$$\left. + 0.053 \left(\frac{V_1}{100} \right)^{2.24} \sin^2 a_1 \left(1 - e_N^2\right) \right] \tag{7}$$

F(T) – temperature function

$$e_T = \frac{V_{2T}}{V_{1T}} = 1.01029 - 1.34759 a_1 + 4.59474 a_1^2 - 6.56109 a_1^3 + 3.05952 a_1^4$$

$$e_N = \frac{V_{2N}}{V_{1N}} = 1.00577 - 1.78169 a_1 + 2.88518 a_1^2 - 2.49243 a_1^3 + 0.76224 a_1^4$$

For first numerical experiments the relationship for the erosion intensity from eq. (7) has been used. Furthermore from the experiments described in section 3 a simpler dependency for the erosion intensity of PF (coal, mean particle diameter d_P = 10.2 μm) on stainless steel has to be derived. For fixed particle velocities the dependency of the erosion intensity on the particle incidence angle E = E (α_1) has to be used in future calculations for prediction of PF erosion.

The time-averaged equations of fluid motion are solved using the program package MISTRAL-3D developed by Perić and Lilek (1992). The program MISTRAL-3D was extensively modified by the authors for gas-particle flow computations. Further modifications involve the implementation of a standard k-ε turbulence model and the parallelisation of the solution algorithm by application of a domain decomposition method. The most fundamental features of MISTRAL-3D are:

- use of non-orthogonal, boundary fitted, numerical grids with arbitrary hexahedral control volumes; use of block structured numerical grids for geometrical approximation of complex flow domains,
- parallelisation using domain decomposition method,
- finite volume solution approach of SIMPLE kind with collocated variable arrangement, Cartesian vector and tensor components,
- acceleration of the iterative solution algorithm by application of the multigrid method.

The solution algorithm for the equations of particle motion is based on the program package Mistral/PartFlow-3D developed by Frank et al. A more detailed description of the 3-dimensional solution algorithm and the developed parallelisation methods for the Lagrangian approach can be found in Frank (2000a and 2000b).

5. PF flow and particle erosion prediction in a flow bifurcator

As an example for the application of the numerical approach we present an application in the area of power engineering. The device of interest is a so-called bifurcator which is used in large coal fired power plants. This bifurcator is belonging to the very complex pipework between coal mills and burners that is necessary to ensure a preferably uniformly distributed supply of the burners with pulverised fuel from the coal mills even in the case when single mills will turn out. Because of the complexity, the pipework consists among other things of a number of bends that cause the emergency of particle ropes mainly as a result of centrifugal forces.

These ropes would influence the distribution of the pulverised fuel to the burners in a negative manner. The result of such an unequal supply of the burners with coal is a lower efficiency and higher output of pollutants and must be avoided. That's why special attention is turned to the disintegration of the ropes. For these purposes the bifurcator contains very complex fixtures called riffle box (see Fig. 6). The riffle box as a whole looks like a house. In detail it consists of a system of 64 differently inclined channels and directly attached to these is a system of vanes that lead the flux alternating to both legs of the bifurcator. If a rope hits the riffle box, it is dispelled by the checkerboard like system of channels in several parts which are then distributed uniformly to both legs because adjacent channels always lead to different legs.

Due to the fact that the bifurcator (riffle box) is designed for the destruction of particle ropes, this part of the PF pipework is extremely exposed to particle erosion. A numerical study has been conducted in order to identify the most erosion affected parts of the bifurcator device, like e.g. guiding vanes and inner fittings.

The construction of a numerical grid is quite difficult because of the complex structure of the riffle box. First of all the against each other inclined 64 channels are a serious problem especially for a structured grid that consists of hexahedrons. So the grid in this region has to split alternating into different branches that pass either a left inclined or a right inclined channel. To realise this, a thin layer between the sets of left and right inclined channels is not belonging to the gridded area and form a thin wall of finite thickness. After the passing of the channels the grid unites again and must map to the guiding vanes which lead alternating to the left and the right leg of the bifurcator and form a triangular structure, which is also difficult to grid with hexahedrons. In this case the triangle is divided into 3 quadrangles. The shape of these quadrangles is determined by the guiding vanes sitting on the triangles that lead either to the right or (alternating) to the left. The position of the guiding vanes marks the block boundaries in the interior of the triangle that cause another difficulty. Since the grid is structured, the subdivisions on the longer (the outside of the triangle) edge are to find on the opposite edge. That means a considerable contraction of the grid within these blocks and simultaneously so-called bad angles that are a general problem in the complex bifurcator geometry.

The discretisation of the geometry results in a grid consisting of up to 4 millions of cells depending on the concrete case of application. The examples differ for instance from the form of the incoming flow region. So the inlet channel geometry had been varied for different real installation conditions of the bifurcator (straight or bended inlet; varying inlet channel length). The predictions were performed on a cluster of 12 PC with Athlon processors running under the operating System LINUX. The input velocity of the basic flow is set to 30 m/s. The particle phase consists of pulverised coal with a density of 1300 kg/m^3. The particles start with the same velocity as the gas flow and are uniformly distributed over the inlet cross section in front of the channel bend. The values for the particle-wall interaction k_W=0.36 and f_W=0.30 for the system of coal particles and a steel wall result from experiments (see section 3). The PF has a particle size distribution of d_P=1 to 13 µm and a mean particle diameter of 10.2 µm.

Results of the computations are shown in Fig. 5 and Fig. 6. The erosion quantities were predicted by tracking of approximately 22.000 particles through the geometry. To obtain a non-uniform distribution of the basic flow and the particle phase in front of the riffle box, a 90 degrees bend is added in the input region. Fig. 5 gives an impression of the erosion of the outer walls in the bifurcating region with the riffle box within. Here white regions represent a maximum of erosion. These are to find, where the cross section narrows and the particles hit the inclined walls. Also the splitting of the particle-stream due to the riffle box is to observe especially on the right leg, where four regions of higher erosion are to observe. The same phenomenon occurs on the backside of the left leg, because the riffle box inside is axisymmetric. The outer wall of the left leg lies behind a guiding vane that leads the stream to the right leg.

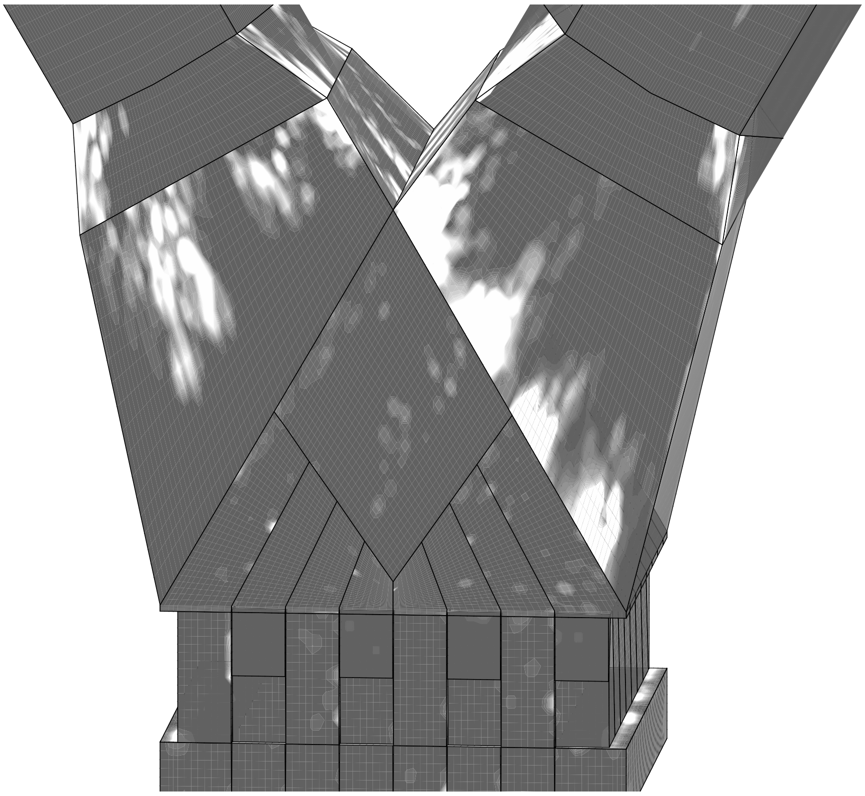


Fig. 5 Erosion of the outer parts in the riffle box region

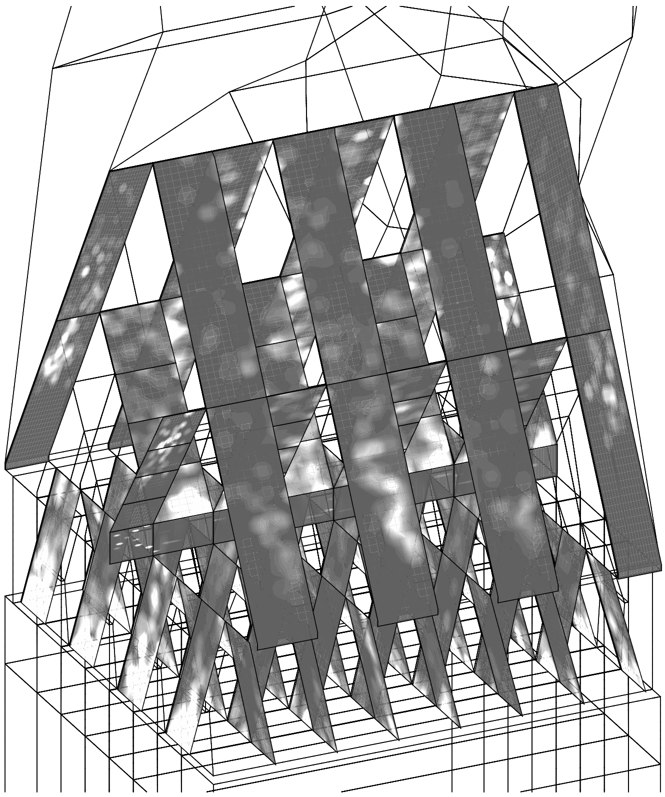


Fig. 6 Erosion of inner parts of the riffle box

The erosion of the riffle box is illustrated by a look to some of the guiding vanes that form this inner part. A remarkable effect is the erosion of the vanes of the lower part of the riffle box. These erode mainly in their lower regions, which were hit by the particles first. In this entry region of the riffle box the main gas-particle flow has not yet adjusted its direction to the inclination of the guiding vanes. So the coal particles hit the guiding vanes in this inlet part of the bifurcator under higher incidence angles and cause higher erosion rates at these locations.

Further downstream the coal particles adjust quickly to the changed flow conditions due to their small particle diameter and the comparable small particle density. The small inertia of PF particles results in very small impact angles for particle-wall collisions on most downstream located parts of the bifurcator and pipe walls. Therefore the caused erosion rates in this parts of the bifurcator are less significant. Only those regions, where the main particle flow isn't oriented yet in direction of the guiding vanes that lead to the left and the right leg respectively are hit from a remarkable quantity of particles under effective angles of attack (shown in Fig. 6) leading to higher erosion rates at this locations.

But it has to be mentioned, that not all of the gas-particle flow phenomena in rope splitting devices are already well understood. Further investigations are necessary to improve device geometry from the point of view of successful rope destruction and particle erosion.

6. Conclusions

A small test facility was presented and used for measurements of the bouncing parameters of coal powder onto a steel wall in dependence of impact velocity and angle. This test facility is useful for erosion measurements too. With experimental data of bouncing process and erosion a numerical simulation of transport of pulverised fuel in a splitting device of the pipework of a coal-fired power plant, a so-called bifurcator with riffle box, was done. The simulation used an Euler-Langrangian approach for gas-particle flows and was performed by parallelisation of the solution algorithm. Besides the fluid and particle flow in the bifurcator device numerically predicted erosion patterns for the outer walls and inner fittings of the riffle box has been predicted from the numerical simulation, showing the most erosion endangered parts of the flow splitting device.

Acknowledgements

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