Article

Numerical Study of the Erosion Process and Transport of Pulverized Coal–Air Mixture in the Mill-Duct System

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Abstract: One of the main causes of damage to the elements of coal-fired boilers installations, leading to breakdowns and, consequently, a shutdown of the block, are erosive processes. Unfortunately, there is not much research conducted on dust erosion of the dust ducts supplying the air–dust mixture to the burners. The problem of erosion of the dust ducts supplying the pulverized coal–air mixture to the burners was presented in this paper. This study was performed for the preliminary feasibility design. The destruction of the material of the dust ducts results in a failure due to erosion, resulting in the mill being shut down from an operation, which in turn may lead to the shutdown of the power plant unit. Therefore, it is important to identify places exposed to pulverized coal erosion. In order to perform calculations, numerical modeling in the commercial program Ansys.Fluent (Ansys Fluent, Computational Fluid Dynamics, Ansys Inc., Pittsburgh, PA, USA) was used. The parameters obtained as a result of laboratory tests were used in the erosion model. The places where erosion is expected are indicated. The highest erosive wear occurred for the M3 mill dust ducts for the case coal 1 and amounted to 45.6 mm/5200 h. On the other hand, the lowest erosive wear occurred for the M2 mill dust ducts powered by coal 3 and amounted to 20.9 mm/5200 h. The identification of places where erosion is expected can be used to protect these places from erosion adequately. Nevertheless, a dispersion threshold should also be placed where there is a high concentration of pulverized coal contributing to increased erosion. The numerical calculations provided information on the velocity of the medium and the behavior of the dust in the dust duct. The numerical calculations also provided information on where dust lacing has occurred. It was shown that coal dust particles with a diameter greater than 100 μm largely erode the dust duct's wall. A model is presented for the calculation of the erosion process to be used in the dust ducts of the power plant.

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1. Introduction

One of the main causes of damage of the elements of coal-fired power boilers installations leading to breakdowns, and consequently to the shutdown of the unit, are erosive processes. Erosion occurs mainly in dust ducts feeding the pulverized coal–air mixture to the burners as well as in the second pass of the boiler on the surfaces of convection bundle tubes. The erosion process is associated with the presence in the continuous phase of particles with a diameter exceeding 25 μm [1]. The erosion rate increases with the exponent of the particle velocity (usually equal to the velocity of the continuous phase) [1–7]. A comparison of this exponent determined experimentally by various researchers is provided in [1,5]. It varies from 2.4 to 3.5 for metal and about 3 for ceramics to 5 for polymers. The exponent of velocity also depends on other parameters, such as particle size and the shape of eroding particles. The value of the velocity exponent also depends on the angle of impact—for steel values lower than 2 (1.4–1.6) at perpendicular inflow [6]. However, the value of the exponent depends on the method of determining the amount of solid phase involved in the process [8]. The exponent of the particle velocity in the erosion equation must be one value higher if you are using concentration μ [kg/m^3] (e.g., [4])

instead of mass flow density of erodent [$\text{kg}/\text{m}^2\text{s}$] (e.g., [9]). Then, the same unit for erosion is obtained. This is due to the requirements for the erosion unit. The rate of metal erosion increases with increasing concentration for small solid-phase concentrations in the gas. For high concentrations, increasing it may not be noticeable in terms of erosive wear, but it can cause a decrease in erosion rate due to collisions between particles flowing into the surface and reflected from it [9]. The erosive defect rate increases with increasing particle size [10]. The shape of the particles also affects erosion. For eroded material made of metal, higher erosion occurs for non-spherical particles with sharp edges. Another factor affecting erosion is the hardness of the erodent particles.

The course of the erosion process largely depends on the type of eroded material. For brittle materials, e.g., cast iron, maximum erosion occurs when the perpendicular impact of solid particles on the surface of the material. In turn, for ductile materials, the erosion rate shows maximum values for the angle of attack (between the tangent to the surface and the particle velocity vector) $\varphi = 20 \div 40^\circ$ [2]. The erosion rate in this area can even be several times higher than for angles φ close to 0° and $75 \div 90^\circ$. In the case of steel, the material most commonly found in boilers, φ values range from about 40° for soft structural steel to about 75° for hardened steel [11].

The flow profile of the operating medium and erodent can be determined by numerical modeling. The source of information about the inflow velocity of the erodent particle in the vicinity of the erosion area is also numerical simulation. In the literature devoted to issues related to the problem of erosion, one can find many different mathematical models whose goal is to convey this process reliably. Wallace and Peters [12] proposed an experimental model of erosion equations for a throttle valve based on the research of Neilson and Gilchrist (1968). In the equation describing erosion, in addition to the angle of impact and erodent velocity, the number of erodent particles, as well as shear and deformation coefficients, was also taken into account. In turn, Finnie et al. [13] proposed an erosion model taking into account only the particle impact angle and the parameter P determined experimentally. Keating and Nesic [14] presented a modification of the Finnie model. They included the erodent particle velocity, the critical velocity for plastic deformation, the density of the eroded material and the yield point in the erosive wear formula. Shirazi et al. [15] described the sand erosion model for the elbow and tee. They proposed determining the erosion rate based on the density of the eroded material, the average number of particles and the eroded surface area. Salam [16] presented a model of erosion in a multiphase flow based on the sand stream, sand grain size, mixture density, geometry-dependent constant and mixture velocity. Wang and Shirazi [17] proposed an erosion model for elbows with a large arc radius, eroded by sand carried by the liquid. The model takes into account the experimental constant for wet surfaces, Brinell hardness for the eroded material, velocity of the erodent particle and the angle of attack function. Chen et al. [18] presented an erosion model based on experimental research for the elbow and tee geometry made of steel and aluminum. Wood et al. [19] referred to the model previously presented by Hashish [20] for small angles of attack of the erodent particle. This model takes into account the material properties of the erodent and eroded surface, as well as the shape of the erodent particle. The tests were carried out for erosion inside the elbow. McLaury et al. [21] experimentally developed an erosion model for steel and aluminum. The model depended on the eroded material used and was created from observations and measurements of the direct impact of the erodent particle (at different angles of attack and velocity) on the eroded surface. The model relates to erosion inside the pipe. Wakeman and Tabakoff [22] conducted tests in a wide range of temperatures (from 10°C to 1093°C) and velocity (from 60 m/s to 450 m/s), as well as using various types of erodent: silica, sand, corundum and ash. The angle at which the erodent particle hits the surface of the eroded material, the angle of reflection and changes in the velocity of the particle were examined. The tests were carried out using a high-speed camera.

Alekhnovich et al. [23] presented the erosive properties of coal dust and fly ash produced from conventional coal dust. The author states that dust consists mainly of

amorphous spheres of high hardness, and its erosive properties are determined by almost all particles except the smallest. Ber et al. [24] performed calculations of pulverized coal erosion of the burners using an erosion model dedicated to sand particles. By using this model, a reliable analysis of the results was presented. Schade et al. [25] determined on the test stand the restitution coefficient, dynamic friction coefficient and tangential velocity losses. The result obtained from the numerical model supported by the experiment predicted erosion patterns of the outer and inner walls of the blast box components, showing the most erosive places of the flow separation device.

Unfortunately, not much research has been conducted on dust erosion of the dust ducts supplying the air–dust mixture to the burners. The article presents the results of numerical calculations of the dust duct erosion process. The erosion model used is based on the parameters obtained as a result of laboratory tests. The places of erosion defects exceeding the thickness of the walls of the dust ducts, which may result in a failure and shutdown of the unit, were indicated.

2. Boundary Conditions and Modeling Description

The mill-duct system consisting of four mills grinding the coal transported with primary air as a pulverized coal–air mixture through a dust duct to the boiler burners is presented in Figure 1. The wall thickness of the dust ducts is 10 mm. For the stable operation of the furnace, it is important to continuously and uninterruptedly supply the pulverized coal–air mixture to the burner in order to burn it [26]. Due to the varied length and geometry of individual dust ducts as well as the associated flow resistance, it is important to maintain proper transport of the pulverized coal–air mixture [27]. The velocity is an important parameter, which should be at the same level for all possible dust ducts to ensure the same flow conditions in the burner. The geometry of the dust duct should be properly selected to prevent pulverized coal torsional lacing in dust ducts [27]. An important risk factor to which dust ducts are exposed is the occurrence of erosion inside of them. In order to locate places particularly exposed to erosion, it is necessary to conduct numerical tests.

Figure 1. The mill-duct system and outline of BP-680 boiler.

Numerical calculations of the pulverized coal–air mixture flow inside the dust ducts were performed together for all six dust ducts for each subsequent mill fed the BP 680 boiler. Numerical tests were realized for three coals differing in residue on the sieve (88 μm and 200 μm), maintaining the same number of polydisperse. The polydispersity number n

characterized the degree of uniformity of the dust grain size. For $n = \infty$, the dust would consist of particles of the same size (monodisperse dust). The number of polydisperse depends on the type of the mill (especially the separator) and the type of milled coal. The higher the number of polydisperse, the smaller the amount of residue on the individual sieves. Thus, the unburnt carbon loss is greater if the boiler is fired with coal with a low polydisperse number n . The particle distribution for the three considered coals as the cumulative standard curves was presented in Figure 2.

Figure 2. Particle distribution for coals.

It was assumed that the distribution of the dust–air mixture is uniform for each of the six dust ducts for a particular mill. As a result, the velocity and intensity of turbulence, assuming an even distribution of the medium, are the same for all six dust ducts for a particular mill (as presented in Table 1). The calculations did not take into account the heat transfer between the medium and the duct wall. Thus, the temperature at the inlets and walls of the dust ducts was not assumed. Operation of the installation at atmospheric pressure was assumed. Differences in ventilation and pulverized coal flow for three coals shown in Table 1 are the results of the different combustion air requirements for these three coals.

Table 1. Input data used for calculations for all six dust ducts for each subsequent mill.

Data.	Unit	Coal 1	Coal 2	Coal 3
Ventilation after the mill	kg/s	18.03	18.73	16.84
Flow of pulverized coal	kg/s	7.79	8.31	7.28
Inlet velocity in one dust duct	m/s	27.0	28.14	25.3
Turbulence intensity	-	3.65	3.63	3.68
Concentration of pulverized coal	kg/m ³	0.396	0.405	0.4
Residue on 88 μm sieve (90)	%	15.0	16.0	14.0
Residue on 200 μm sieve	%	0.48	0.58	0.40
The average diameter	μm	53	54	52
Number of polydisperse	-	1.26	1.26	1.26

Along with the change in coal, the ventilation and the pulverized coal mass flow changed. The data necessary to perform the calculations are summarized in Table 1. The geometric model and the numerical mesh were created in the commercial CFD Ansys.Fluent program and shown in Figure 3. The hexahedral mesh, which consists of about 495,056 numerical cells for every six dust ducts from a particular mill, was used in the model. Erosion was calculated for one hour using the erosion model presented in [28].

Figure 3. Numerical mesh and geometrical model for pulverized coal ducts for mill 1, mesh for individual ducts and for 4 mills.

The mesh was refined using the mesh adaptation option. Adaptation of the distance function and velocity value was used. The stages of the mesh refinement using an example of an inlet are shown in Figure 4.

Figure 4. Stages of mesh refinement using an example of an inlet.

In order to check the adequacy of the applied mesh resolution, a mesh independence study was conducted. For this purpose, five types of meshes differing in the number of numerical cells were checked: 0.2 million, 0.3 million, 0.5 million, 1 million and 2 million. The predicted pressure drop and erosion in the six ducts of the model are presented in Figure 5.

Figure 5. Change in pressure drop [Pa] and erosion [kg/m²s] predicted by different meshes.

The pressure drop is marked as dp for the individual six ducts shown in Figure 5. The large divergence in the results for 0.2 and 0.3 million cells in relation to the results obtained for the finest mesh was observed for the pressure drop and erosion. The mesh independence study against erosion and pressure drop in dust ducts showed that the results confirm the tendency to approach the values obtained for mesh consisting of 1 and 2 million cells. For all dust ducts, there was no increase in erosion as well as pressure drop with the increase in the number of numerical cells. Therefore, considering the overall aspect, it was found that the 0.5 million cell mesh was chosen as a compromise between accuracy and computation time. Calculations were not made on fine meshes due to hardware and time constraints.

The large viscosity gradients in turbulent flows in the wall region occurred. Therefore, the mesh should be compacted in the area of the boundary layer in order to simulate turbulent flows limited by walls correctly. The $k-\epsilon$ turbulence model does not predict the flow correctly in the boundary layer. In order to deal with this phenomenon, in the area of the boundary layer, the mesh was compacted, and an appropriate wall function was used. The compaction of the mesh near the wall, i.e., where there was a boundary layer, improved the velocity profile in this area, which, in turn, contributed to the credibility of the erosion process of the dust duct wall. For dust ducts of mill 1 and for coal 1, calculations were carried out in order to obtain the required Y^+ parameter. The calculations were performed using the k -epsilon turbulence model with non-equilibrium wall functions. For the obtained results to be considered correct, the Y^+ parameter should be greater than 30 and less than 300. The Y^+ parameter for selected dust ducts for mill 1 is presented in Figure 6.

Figure 6. The Y^+ parameter for selected dust ducts from mill 1 for coal 1.

The finite volume method was used to discretize the mesh. As a result of discretization, differential equations were replaced with a system of algebraic equations that can be solved numerically. In spatial discretization for momentum, the more accurate Second-Order discretization scheme was used. For turbulent kinetic energy and turbulent dissipation rate, the First-Order Upwind scheme was used, as it is easier to converge, in order to shorten the computation time and due to hardware limitations. However, the PRESTO scheme was chosen for the pressure discretization. The least-squares cell-based procedure was selected for gradient evaluation. The SIMPLE scheme for pressure–velocity coupling was used. The gas-phase flow was modeled in Euler coordinate system [12,15,21,28,29]. In modeling turbulent flow, it is necessary to solve the Navier–Stokes equations. The RANS (The Reynolds-averaged Navier–Stokes) approach was chosen to perform the calculations, in

which the behavior equations are formulated for time averages of temperature, pressure and velocity. The RANS approach is characterized by a good compromise between the quality of mapping phenomena and the required hardware resources. The k - ϵ real turbulence model with the “non-equilibrium wall functions” option was used to take into account the effect of pressure gradients [12,29–32]. It introduces two additional equations that close the system, although the introduction of additional boundary conditions is required. This model introduces two new variables—kinetic energy of turbulence (k) and energy dissipation (ϵ). As a result, it enables the determination of the turbulent viscosity (μ_t), which is responsible for the increase in viscosity at turbulent flows. Two transport equations must be solved simultaneously with the mass, momentum and energy balance equations. The modeled transport equations for k and ϵ are as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(u + \frac{u_t}{\sigma_k} \right) \frac{\partial}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_j}(\rho \epsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(u + \frac{u_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \rho C_1 S \epsilon - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b + S_\epsilon, \quad (2)$$

In the above equations, G_k represents the generation of turbulence kinetic energy due to the velocity gradient, G_b is the generation of turbulence kinetic energy caused by buoyancy, Y_M represents the effect of dilatation fluctuations in compressible turbulence on the overall dissipation factor, C_2 and $C_{1\epsilon}$ are constants and σ_k and σ_ϵ are appropriate Prandtl numbers for k and ϵ .

In turn, the flow of the moving particle was modeled in the Lagrange approach by traveling analysis, i.e., calculating the trajectories of moving particles [12,13,21,29,33,34]. The Discrete Phase Model (DPM) was used to simulate the flow of fuel particles. It predicts the trajectories of single particles described by Lagrange’s theory. The model tracks changes in the properties of particles moving in the computational domain. This model enables the determination of physical quantities such as temperature and velocity at any point in the trajectory. For turbulent flow, it predicts trajectories, using the mean fluid velocity $\bar{u}$ in the particle trajectory equation:

$$\frac{du_p}{dt} = F_d(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} \quad (3)$$

The first part of this equation is responsible for the friction force, the second for the force of gravity.

$$F_d = \frac{18\mu}{\rho_p d_p^2} \frac{C_D Re}{24} \quad (4)$$

$$Re = \frac{\rho d_p (u_p - u)}{\mu}, \quad (5)$$

where u is the flow velocity, u_p is the particle velocity, μ is the fluid dynamic viscosity, ρ is the fluid density, ρ_p is the particle density, d_p is the particle diameter, Re is the relative Reynolds number and C_D is the drag coefficient depending on the particle shape.

The interaction between pulverized coal particles (particle–particle interactions) was not taken into account in the numerical calculation. However, the interaction between solid and continuous phases by mass, energy and momentum exchange due to the two-way approach was taken into account. Unsteady solid-phase feeding was introduced at steady gas-phase flow. In order to calculate the dispersion of particles resulting from the effects of gas turbulence, a stochastic model was used. The Rosin–Rammmler–Sperling distribution and the non-spherical shape of the fuel particles were used [35]. In the model, the particles were treated as reflected after colliding with the wall. The Assumption of the numerical model was presented in Table 2. In order to predict the trajectory of reflected particles, it was necessary to use the coefficients of restitution e_t and e_n . The restitution coefficients

in the reflection model make it possible to predict the trajectory of erosive particles after reflection from the surface. These coefficients are determined by measuring the angle of attack α_1 of the erodent on the eroded surface and measuring the attack velocity w_1 as well as rebound velocity of the erodent w_2 (Figure 7).

Table 2. Assumption of numerical model.

Two-phase model	Euler–Lagrange
Turbulence model	k- ϵ non-equilibrium wall functions
Flow field	SIMPLE
No particle–particle interactions	
Two-way approach: interaction between particle and continuous phases (mass, energy, momentum exchange)	
Unsteady particle phase	
Steady gas phase	
Stochastic model for dispersion of particles	
The Rosin–Rammler–Sperling distribution for particles	
Non-spherical shape of the particles	
Particle treated as reflected after a particle–wall collision

Figure 7. Scheme of particle reflection with components of velocity and the angles.

Normal restitution coefficient is defined as:

$$e_n = \frac{w_{2n}}{w_{1n}} = \frac{w_{2n}}{w_1 \sin \alpha_1}, \quad (6)$$

while the tangential coefficient as:

$$e_t = \frac{w_{2t}}{w_{1t}} = \frac{w_{2t}}{w_1 \cos \alpha_1}, \quad (7)$$

where:

w_n is the normal component of velocity relative to surface;

w_t is the tangential component of velocity in relation to the surface;

e_n is the normal coefficient of restitution defined as the sum of momentum in the normal direction generated by the particle in relation to the surface;

e_t is the tangential restitution coefficient defined as the sum of momentum in a tangential direction generated by a particle in relation to the surface.

A normal or tangential restitution coefficient equal to 1 means that the particle retains normal or tangential momentum after reflection (elastic collision). While a coefficient equal to 0 means a perfectly plastic (inelastic) collision. In fact, for a real or elastic–plastic collision, this factor is in the range $0 < e < 1$. Research shows that the angle of attack of the erodent particle has a significant impact on the restitution coefficients. Restitution coefficients are defined in the Ansys.Fluent program as a function of the angle of attack α_1 . Thus, these coefficients indirectly affected the result of the erosion rate calculations. However, they do not appear directly in the erosion model used in code. Various correlations are proposed

in the literature to describe the restitution coefficients [36,37]. The restitution coefficients were introduced to the model in the boundary conditions of the dust duct walls as constant. This is due to the fact that in the laboratory of the Department of Power Engineering and Turbomachinery at Silesian University of Technology, they were tested at an angle of 45° because, for this angle, the highest erosion occurs for steel. The purpose of the calculations was to show the greatest erosion loss in the dust ducts in order to identify the places most exposed to erosion [38]. The normal coefficient of restitution $e_n = 0.46$ and the tangential restitution coefficient $e_t = 0.73$. In this study, the Edwards and McLaury erosion model [28] was used similar to this paper [24], which is described by the following equation:

$$E = A w_e^n f(\alpha) \left[\text{kg}_{\text{mat}}/\text{m}^2 \right], \quad (8)$$

where:

$$A = 15.59 \times 10^{-7} B^{0.59} F_s, \quad (9)$$

F_s is the erodent particle shape factor;

w_e is the erodent's velocity, m/s;

n is the exponent of the velocity;

$f(\alpha)$ is the function describing the effect of angle of attack of erodent particles on the erosion rate;

B is the Brinell hardness.

For irregular particle shape factor, F_s equals 1; for semi-rounded particle, it is 0.53; and for a fully rounded particle, it is 0.2 [28]. For the coal particle, a shape factor of 0.53 was considered. There are several ways to describe the function of the angle of attack for the erodent particle hit the eroded surface in relation to the flow direction of the medium [15,28,39]. In this study, this function was implemented into the model in the boundary conditions of the wall as a polynomial and was adopted as [28]:

$$\text{for } \alpha \leq 15^\circ, \quad f(\alpha) = -33.4\alpha + 17.9\alpha^2 \quad (10)$$

$$\text{for } \alpha > 15^\circ, \quad f(\alpha) = 1.239\cos^2\alpha\sin\alpha - 0.1192\sin^2\alpha + 2.167 \quad (11)$$

3. Results and Discussion

It was also noted in [18,28,40,41] that with the increase in velocity and the change in the bending angle of the elbow, the erosive wear increases. A sudden change in the direction of flow contributes to the heterogeneous flow of pulverized coal, causing a local increase in its concentration in the transporting medium, i.e., air (Figure 8). In the case of a double change in flow direction and additionally rotated flow around the axis of the duct, pulverized coal lacing is created (Figure 8). A similar phenomenon was noticed in [27,42]. The larger the particle diameter, the higher the susceptibility to centrifugal forces and the inertia related to the airflow (Figure 8). Therefore, pulverized coal particles with a diameter larger than $100 \mu\text{m}$ largely erode the wall of the dust duct. In the area of the elbow of the dust duct, where the pulverized coal velocity increases due to a sharp change in the direction of the particles, the erosion process usually occurs (Figures 9–20).

Selected results of numerical calculations of pulverized coal velocity and erosion of dust duct after 1 h were presented in the below figures.

The velocities of pulverized coal particles in the dust ducts for individual coals for a particular mill differed. This is due to the different ventilation and pulverized coal mass flow, and thus the different particle velocities at the inlet to individual dust ducts. The highest velocity at the inlet to the dust ducts occurred for the case coal 2 (Table 1). In this case, it resulted in the highest velocities of pulverized coal particles in the dust duct elbows, for example, the dust duct of the mill M1 (Figure 10). However, the lowest velocity occurred for the case of coal 3 (Table 1), which, in turn, translates into the lowest velocities in the elbows for this case, for example, the dust ducts of the mill M1 (Figure 11). Different velocities for individual dust ducts from a particular mill resulted from different geometries

of the dust pipes, for example, the dust ducts of the mill M1 (Figure 9). The various geometry results from the different distances between the outlet from the mill separator and the burner for individual dust ducts. As a result of differentiation in geometry, there are different bend angles of the elbows and straight sections of different lengths, called run-up sections, aimed at unifying the velocity profile of the gaseous medium. More elbows with a large bend angle as well as changes in the direction of the flow of the medium in the dust duct made the pulverized coal more susceptible to twisting, creating lacing. This phenomenon was occurred more in the dust ducts of the mill M1 than in the dust ducts of the mill M4. The highest velocities in the dust duct, equal to 2.74 m/s, were obtained for the mill M1 powered by coal 2. However, the lowest velocities, equal to 2.37 m/s, were obtained for the mill M2 powered by coal 3.

Figure 8. Fragment of pulverized coal channel M1 powered by coal 1 presenting the velocity [m/s] and diameter of individual coal dust particles [μm].

Figure 9. Pulverized coal particle velocity [m/s] and erosion of the channel [$\text{kg}/\text{m}^2\text{s}$], M1, coal 1.

Figure 10. Pulverized coal particle velocity [m/s] and erosion of the channel [kg/m²s], M1, coal 2.

Figure 11. Pulverized coal particle velocity [m/s] and erosion of the channel [kg/m²s], M1, coal 3.

Figure 12. Pulverized coal particle velocity [m/s] and erosion of the channel [kg/m²s], M2, coal 1.

Figure 13. Pulverized coal particle velocity [m/s] and erosion of the channel [kg/m²s], M2, coal 2.

Figure 14. Pulverized coal particle velocity [m/s] and erosion of the channel [kg/m²s], M2, coal 3.

Figure 15. Pulverized coal particle velocity [m/s] and erosion of the channel [kg/m²s], M3, coal 1.

Figure 16. Pulverized coal particle velocity [m/s] and erosion of the channel [kg/m²s], M3, coal 2.

Figure 17. Pulverized coal particle velocity [m/s] and erosion of the channel [kg/m²s], M3, coal 3.

Figure 18. Pulverized coal particle velocity [m/s] and erosion of the channel [kg/m²s], M4, coal 1.

Figure 19. Pulverized coal particle velocity [m/s] and erosion of the channel [kg/m²s], M4, coal 2.

Figure 20. Pulverized coal particle velocity [m/s] and erosion of the channel [kg/m²s], M4, coal 3.

The photo of the eroded dust duct is shown in Figure 21 [43]. The areas of the failure in the wall of the dust duct resulting from the action of dust erosion are visible. Pulverized coal erosion poses a real threat to shut down the unit from the operation.

Figure 21. Sections of dust duct fully damaged as a result of erosion, reproduced with permission from [43], Elsevier, 2022.

In order to present erosion as a decrease in material thickness over time, the erosion model was modified to the following form:

$$ER = \frac{E}{\rho_m} \cdot 1000 \text{ [mm/h]} \quad (12)$$

The annual operation time of the boiler in a power plant is 5200 h. The time of 5200 h is the time of operation of the boiler in a power plant during the calendar year. It results from taking into account planned (repairs) and unplanned (breakdowns) shutdowns. Due to the hardware requirements and the time needed to calculate the erosion after 5200 h, it was decided to calculate the erosion for 1 h. A linear course of the erosion process was assumed. It was numerically tested whether a particular dust duct is able to work the prescribed working time of 5200 h without failure. Therefore, Table 3 shows the effects of erosion after 5200 h. The erosion results for several time periods based on linear erosion progression were also presented in Table 3. After this time, in each considered dust duct, the wall of the dust pipe with a thickness of 10 mm was damaged/punctured. The time after which a wall of 10 mm would be pierced for a particular mill and coal, resulting in failure and putting the unit out of service, was summarized in Table 3. As can be seen

from Table 3 and the figures presented above, despite the seemingly small differences in granulation for coals 1, 2 and 3 (difference in residue on the 90 sieve max 2%, while the difference in residue on the 200 sieve max 0.18% (Table 1)) erosive defect is significant. For example, consider coals 1 and 2 for the M2 mill, for which there is a comparable velocity in the dust duct (resulting from ventilation). The difference between them is about 8 mm (6500 h to failure), i.e., a value dangerously approaching the wall thickness of the dust duct.

Table 3. Maximum erosion loss of the wall after 5200 h and erosion loss for different times.

Mill	Coal	Erosion [mm/5200 h]	Time to Failure [h]	Time to Failure [day]	Day [mm]	Week [mm]	Month [mm]
M1	1	27.19	1911.9	80	0.13	0.88	3.77
	2	24.02	2164.4	90	0.11	0.78	3.33
	3	23.05	2255.6	94	0.11	0.74	3.19
M2	1	32.12	1619.0	67	0.15	1.04	4.45
	2	23.83	2182.1	91	0.11	0.77	3.30
	3	20.92	2486.1	104	0.13	0.94	4.02
M3	1	45.59	1140.6	48	0.21	1.47	6.31
	2	42.29	1229.7	51	0.20	1.37	5.86
	3	31.6	1645.5	69	0.15	1.02	4.38
M4	1	31.79	1635.4	68	0.15	1.03	4.40
	2	26.42	1968.1	82	0.12	0.85	3.66
	3	21.69	2397.0	100	0.10	0.70	3.00

In general, erosive wear is influenced by the velocity and diameter of the erodent, the geometry of the dust ducts, the angle of attack and the possible occurrence of dust lacing, which increases the dust concentration locally. Thus, for all mills, the highest erosive wear can be observed for the case coal 1. Coal 2 had a higher maximum velocity than case coal 1, but for coal 1, there was less residue on the 200 and 90 sieves (Table 1). There are more erosive particles for coal 1 than for coal 2. When comparing the installations operated with coal 1 and 3, the situation is different. There are more erosive particles for case coal 3 than for coal 1, but the velocity for case coal 1 is definitely higher than for case coal 3.

Differences for individual mills result from different lengths of dust ducts and geometry—a number of elbows, different angles of knee bends and thus different angles of erodent incidence on the duct wall. Thus, the highest erosive wear occurred for the M3 mill dust ducts, then for the M2 mill dust ducts, and later for the M4 mill. The lowest erosion was in the dust ducts of the M1 mill.

The highest erosive wear was recorded for dust ducts of the mill M3 powered by coal 1 and amounted to 45.6 mm/5200 h. It will lead to a breakdown resulting in a stoppage of the mill after 48 days of operation. On the other hand, the lowest erosive wear was occurred for the dust ducts of the mill M2 powered by coal 3 and amounted to 20.9 mm/5200 h. As a result, due to an erosive failure, the mill would shut down after 104 days of operation.

Therefore, in the period of operation of the unit in the power plant of 5200 h, i.e., about 217 days, with such erosion progressing, failure due to erosion should be expected more than two times for the dust ducts of the mill M2 powered by coal 2 and coal 3 and for dust ducts of the mill M4 powered by coal 2 and coal 3, as well as and for the dust ducts of the mill M1 fed with all three coals. On the other hand, one would expect erosion failures more than three times for dust ducts of the mill M2 fed by coal 1, for the mill M3 fed by coal 3 and for mill M4 fed by coal 1. One would expect failure more than four times due to erosion for the dust ducts of the mill M3 powered by coal 2 and coal 3.

In order to prevent breakdowns and stoppages in supplying the pulverized-air mixture to the burners, and thus shutting down the boiler, the places exposed to erosion should be protected with a suitable material resistant to erosion.

4. Conclusions

Numerical calculations provided information on the velocity of the pulverized coal–air mixture and the behavior of pulverized coal in the dust duct. The highest velocities of pulverized coal particles in the dust duct elbows occurred for the mill fed by coal 2. However, the lowest velocities of pulverized coal particles in the elbows were recorded for the mill fed by coal 3. The pulverized coal was more lacing in the dust ducts of the mill M1 than in the dust ducts of the mill M4. The highest velocities in the dust duct, equal to 2.74 m/s, were obtained for the mill M1 powered by coal 2. However, the lowest velocities, equal to 2.37 m/s, were obtained for the mill M2 powered by coal 3. Thus, for all mills, the highest erosive wear can be observed for the case coal 1. The highest erosive wear occurred for dust ducts of the mill M3 powered by coal 1 and amounted to 45.6 mm/5200 h. It leads to a breakdown resulting in a stoppage of the mill after 48 days of operation. On the other hand, the lowest erosive wear occurred for the dust ducts of the mill M2 powered by coal 3 and amounted to 20.9 mm/5200 h. As a result, due to erosive failure, the mill would be shut down after 104 days of operation. During the unit operation period in the 5200 h power plant, i.e., about 217 days with progressive erosion, more than 2 to 4 times failure due to erosion should be expected for the dust ducts of the four mills in question, powered by three selected coals. Therefore, in order to prevent breakdowns and stoppages in the supply of dust–air mixture to the burners, and thus shutdown of the boiler, places exposed to erosion should be protected with a suitable material resistant to erosion. Nevertheless, the scattering threshold should also be placed where a high concentration of pulverized coal contributes to increased erosion. The article showed that numerical tests of the pneumatic transport process of the pulverized coal–air mixture in dust ducts provided information on the erosion of dust ducts as well as the profile of velocity. Numerical tests are a valuable source of information that allows avoiding design errors during modernization, providing the opportunity to analyze many possible variants of design solutions and ultimately select the best one.

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Nomenclature

B	Brinell hardness
e_n	normal coefficient of restitution
e_t	tangential restitution coefficient
E	erosion rate ($\text{kg}_{\text{mat}}/\text{m}^2$)
ER	modified erosion rate (mm/h)
$f(\alpha)$	function of the angle of attack of erosive particles
F_s	erodent particle shape factor
n	polydispersity number
n	exponent of the velocity
w_1	velocity of attack of the erodent (m/s)
w_2	velocity of reflection of the erodent (m/s)
w_e	erodent's velocity (m/s)
w_n	normal component of velocity relative to surface (m/s)
w_t	tangential component of velocity in relation to the surface (m/s)
α_1	angle of attack of the erodent
α_2	reflection angle of the erodent
ρ_m	density of the eroded surface (kg/m^3)

References

1. Foster, D.J.; Livingston, W.R.; Wells, J.; Williamson, J.; Gibb, W.H.; Bailey, D. *Particle Impact Erosion and Abrasion Wear—Predictive Methods and Remedial Measures*; Report No. R241 DTI/Pub URN 04/701; Mitsui Babcock: Renfrew, UK, 2004.
2. Raask, E. *Erosion Wear in Coal Utilisation*; Hemisphere Publishing Corporation: London, UK, 1988; ISBN 3-540-18601-8.
3. Кузнецов, Н. Золотой износ труб и предельно допустимые скорости газов в котельных агрегатах. *Теплоэнергетика* **1955**, *4*.
4. Świrski, J. Research on ash erosion and evaluation of boiler pipes wear as a result of its operation. In *Works of the Institute of Power Engineering*; Institute of Power Engineering: Warszawa, Poland, 1975; Volume 1. (In Polish)
5. Meuronen, V. *Ash Particle Erosion on Steam Boiler Convective Section*; Research Papers 64; Lappeenranta University of Technology: Lappeenranta, Finland, 1997.
6. Uetz, H. Strahlverschleiß. *Mitteilungen der VGB* **1969**, *49*, 50–57.
7. Pronobis, M. *Modernization of Power Boilers*; WNT: Warszawa, Poland, 2013. (In Polish)
8. Fehndrich, W. Verschleißuntersuchungen an Kesselrohren. *Mitteilungen der VGB* **1969**, *49*, 58–64.
9. Parslow, G.I.; Stephenson, D.J.; Strutt, J.E.; Tetlow, S. Paint layer erosion resistance behavior for use in a multilayer paint erosion indication technique. *Wear* **1997**, *212*, 103–109. [\[CrossRef\]](#)
10. Zhang, L.; Sazonov, V.; Kent, J.; Dixon, T.; Novozhilov, V. Analysis of boiler-tube erosion by the technique of acoustic emission. Part I. Mechanical erosion. *Wear* **2001**, *250*, 762–769. [\[CrossRef\]](#)
11. Heiermann, G.; Langner, H.; Brinkmann, C.; Mondry, H. *Konstruktionskriterien zur Erosionsminderung in Wirbelschichtfeuerungen*; Wirbelschichtfeuerung und Dampferzeugung: Essen, Germany, 1988.
12. Wallace, M.S.; Peters, J.S. CFD based erosion modeling of multi-orifice choke valve. In Proceedings of the 2000 ASME Fluids Engineering Summer Meetings, Boston, MA, USA, 11–15 June 2000.
13. Finnie, I.; Stevick, G.R.; Ridgely, J.R. The influence of impingement angle on the erosion of ductile metals by angular abrasive particles. *Wear* **1992**, *152*, 91–98. [\[CrossRef\]](#)
14. Keating, A.; Nesic, S. Particle tracking and erosion prediction in three-dimensional bends. In Proceedings of the FEDSM2000, ASME Fluids Engineering Summer Meeting, Boston, MA, USA, 11–15 June 2000.
15. Shirazi, S.A.; Shadley, J.R.; McLaury, B.S. A procedure to predict solid particle erosion in elbows and tees. *J. Press. Vessel. Technol.* **1995**, *117*, 45–52. [\[CrossRef\]](#)
16. Salam, M.M. An alternative to API 14 E erosion velocity limits for sand laden fluids. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 4–7 May 1998; pp. 721–731.
17. Wang, J.; Shirazi, S.A. A CFD based correlation for erosion factor for long-radius elbows and bends. *Trans. ASME* **2003**, *125*, 26–34. [\[CrossRef\]](#)
18. Chen, X.; McLaury, B.S.; Shirazi, S.A. Application and experimental validation of a computational fluid dynamics (CFD) based erosion prediction model in elbows and plugged tees. *Comput. Fluids* **2004**, *33*, 1251–1272. [\[CrossRef\]](#)
19. Wood, R.J.K.; Jones, T.F.; Ganeshalingam, J.; Miles, N.J. Comparison of predicted and experimental erosion estimates in slurry ducts. *Wear* **2004**, *256*, 937–947. [\[CrossRef\]](#)
20. Hashish, M. An improved model of erosion by solid particle impact. In Proceedings of the 7th International Conference on Erosion by Liquid and Solid Impact, Cambridge, UK, 7–10 September 1987; pp. 66–69.
21. Edwards, J.K.; McLaury, B.S.; Shirazi, S.A. Supplementing a CFD Code with Erosion Prediction Capabilities. In Proceedings of the ASME FEDSM'98: ASME 1998 Fluids Engineering Division Summer Meeting, Washington, DC, USA, 21 May–15 June 1998.
22. Tabakoff, W.; Wakeman, T. Measured particle rebound characteristics useful for erosion prediction. In *Turbo Expo: Power for Land, Sea, and Air*; ASME paper 82-GT-170; American Society of Mechanical Engineers: New York, NY, USA, 1982.
23. Alekhnovich, A.N. Erosive Properties of Pulverized Coal Fly Ash (Review). *Power Technol. Eng.* **2021**, *55*, 396–403. [\[CrossRef\]](#)
24. Ber, L.D.; Karimi, S.; Shirazi, S.A. Application of a Mechanistic Erosion and Abrasion Model to Pulverized Coal (PC) Injections. In Proceedings of the ASME 2021 Power Conference POWER 2021, online, 20–22 July 2021. [\[CrossRef\]](#)
25. Schade, K.-P.; Erdmann, H.-J.; Hadrich, T.; Schneider, H.; Frank, T.; Bernert, K. Experimental and numerical investigation of particle erosion caused by pulverised fuel in channels and pipework of coal-fired power plant. *Powder Technol.* **2002**, *125*, 242–250. [\[CrossRef\]](#)
26. Love, A.I.J.; Giddings, D.; Power, H. Numerical analysis of particle flows within a double expansion. *Powder Technol.* **2014**, *266*, 22–37. [\[CrossRef\]](#)
27. Borsuk, G.; Dobrowolski, B.; Wydrych, J. The use of numerical methods in the design and operation of pneumatic transport systems. *Logistyka* **2014**, *6*, 2227–2236. (In Polish)
28. Edwards, J.K.; McLaury, B.S.; Shirazi, S.A. Evaluation of alternative pipe bend fittings in erosive service. In Proceedings of the ASME FEDSM'00: ASME 2000 Fluids Engineering Division Summer Meeting, Washington, DC, USA, 11–15 June 2000.
29. Sciubba, E.; Zeoli, N. A Study of Sootblower Erosion in Waste-Incinerating Heat Boilers. *J. Energy Resour. Technol.* **2007**, *129*, 50–53. [\[CrossRef\]](#)
30. Picart, A.; Berlemont, A.; Gouesbet, G. Modeling and predicting turbulence fields and the dispersion of discrete particles transported by turbulent flows. *Int. J. Multiph. Flow* **1986**, *12*, 237–261. [\[CrossRef\]](#)
31. Shih, T.; Liou, W.W.; Shabbir, A. A new κ - ϵ eddy viscosity model for high Reynolds number turbulent flows—Model development and validation. *Comput. Fluids* **1995**, *24*, 227–238. [\[CrossRef\]](#)

32. Afolabi, L.; Aroussi, A.; Isa, N.M. Numerical modelling of the carrier gas phase in a laboratory-scale coal classifier model. *Fuel Processing Technol.* **2011**, *92*, 556–562. [\[CrossRef\]](#)
33. Kozić, M.; Ristić, S.; Puharić, M.; Linić, S. CFD Analysis of the Influence of Centrifugal Separator Geometry Modification on the Pulverized Coal Distribution at the Burners. *Trans. FAMENA* **2014**, *38*, 25–36.
34. Vuthaluru, H.B.; Pareek, V.K.; Vuthaluru, R. Multiphase flow simulation of a simplified coal pulveriser. *Fuel Processing Technol.* **2005**, *86*, 1195–1205. [\[CrossRef\]](#)
35. Hernik, B. Research to Reduce the Risk of Corrosion and Erosion of Boilers. Ph.D. Thesis, Silesian University of Technology IMiUE, Gliwice, Poland, 2009. (In Polish).
36. Forder, A.; Thew, M.; Harrison, D. A Numerical Investigation of Solid Particle Erosion Experienced Within Oilfield Control Valves. *Wear* **1998**, *216*, 184–193. [\[CrossRef\]](#)
37. Grant, T.; Tabakoff, W. Erosion prediction in turbomachinery resulting from environmental solid particles. *J. Aircraft* **1975**, *12*, 471–547. [\[CrossRef\]](#)
38. Hernik, B.; Pronobis, M.; Wejkowski, R.; Wojnar, W. Experimental verification of a CFD model intended for the determination of restitution coefficients used in erosion modelling. *E3S Web Conf.* **2017**, *13*, 05001. [\[CrossRef\]](#)
39. Ahlert, K. Effects of Particle Impingement Angle and Surface Wetting on Solid Particle Erosion on AISI 1019 Steel. Master's Thesis, University of Tulsa, Tulsa, OK, USA, 1994.
40. Dobrowolski, B.; Wydrych, J. Evaluation of numerical models for prediction of areas subjected to erosion wear. *Int. J. Appl. Mech. Eng.* **2006**, *11*, 735–749.
41. Karimi, S.; Siamack, S.A.; McLaury, B.S. Predicting fine particle erosion utilizing computational fluid dynamics. *Wear* **2017**, *376–377*, 1130–1137. [\[CrossRef\]](#)
42. Okafor, E.; Ibeneme, I.O. Parametric Analysis of Sand Erosion in Pipe Bends Using Computational Fluid Dynamics. *Int. J. Sci. Eng. Sci.* **2019**, *3*, 60–65.
43. Zdravecká, E.; Šlota, J.; Tkáčová, J. Erosive failure of steel pipeline by solid pulverized particles. *Eng. Fail. Anal.* **2014**, *46*, 18–25. [\[CrossRef\]](#)