# NUMERICAL SIMULATION OF MULTIPHASE FLOW IN VENTILATION MILL AND CHANNEL WITH LOUVERS AND CENTRIFUGAL SEPARATOR

### by

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This paper presents the results of numerical flow simulation in ventilation mill of Kostolac B power plant, where louvers and centrifugal separator with adjustable blade angle are used. Numerical simulations of multiphase flow were performed using the Euler-Euler and Euler-Lagrange approach of ANSYS FLUENT software package. The results of numerical simulations are compared with measurements in the mill for both types of separators. Due to very complex geometry and large number of the grid cells, convergent solution with the Eulerian model could not be obtained. For this reason the mixture model was employed resulting in very good agreement with measurements, concerning the gas mixture distribution and velocity at the main and secondary burners. There was large difference between the numerical results and measurements for the pulverized coal distribution at the burners. Taking into consideration that we analyzed dilute mixture with very low volume fraction of the coal, the only choice was the Euler-Lagrange approach, i. e. discrete phase model limited to volume fraction of the discrete phase less than 10-12%. Obtained distributions of the coal at the burners agree well for both types of separators.

Key words: ventilation mill, computational fluid dynamics, multiphase flow, Euler-Euler approach, mixture model, Euler-Lagrange approach

### Introduction

Ventilation mill is a very important system and its operation has a significant influence on the level of a power plant efficiency. The character of the multiphase flow in the ventilation mill, where recirculation gases, pulverized coal, sand, and other materials are included, is directly related to the efficiency of the ventilation mill [1-3]. The construction of the ventilation mill, the geometry of the mixture channel, and wear of the vital parts are of great significance to the energy efficiency of the plants.

In Kostolac B power plant (Kostolac, Serbia), there are two types of separators in the ventilation mills, either louvers or centrifugal separator with adjustable blade angles. In

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2003 the reconstruction was accomplished, when the centrifugal separators were replaced with the louvers in four of eight channels, so the odd numbered mills have channels with louvers, whereas even ones are with the centrifugal separators.

Multidisciplinary researches of the ventilation mills and the mixture channel include a variety of theoretical, numerical, empirical and experimental methods [4-25]. Specific measurements conditions often cause failure of measuring equipment, so contactless measuring methods or measurements on laboratory models are introduced in a greater extent. Numerical simulation of the flow is the most economical, fastest, and very reliable method in analyzing the complex issues of the multiphase flow and its optimization.

The examples of the multiphase flow numerical simulation in various power plants can be found in the available literature. The numerical methods are used to simulate the flow field in coal preparation plants, mills, mixture channel, and burners [6-8]. Although the results of the numerical simulation are obtained for Kostolac B power plant, they are of importance in bringing more general conclusions about the qualitative and quantitative parameters of the mixture in the similar plants.

The importance of the research, that is subject of the paper, should be viewed in the context of both the operation of thermal power plants and energy situation in general. Every contribution to the energy efficiency of thermal power plants, the energy saving and the environmental protection is a significant result.

This paper presents the results of numerical simulations of multiphase flow in the real system, consisted of the ventilation mill and mixture channel of Drmno Kostolac B power plant [1, 9]. The flow through the mill duct systems with the louvers and centrifugal separator is considered. The results of the numerical simulations are compared with the measurements in the mill thermal plant [2, 24, 25].



Figure 1.Ventilation mill in Kostolac B thermo power plant

### Ventilation mill

In Kostolac B power plant, the coal is pulverized in the ventilation mills. The system includes eight ventilation mills of EVT N 270.45 type, with a nominal capacity of 76 t/h of coal. Each mill is directly connected to the burner system consisted of four levels. Two main burners are at the lower levels, while the secondary ones are at the upper level. In fig. 1 a photo of the mill-duct system is given.

The project foresaw the distribution of the coal powder to be 70%:30% for the main and secondary burners, respectively. Simultaneously, the distribution of the gas mixtures was supposed to be 50%:50%. Some reconstructions of the system were performed in order to increase the ventilation effect, mill capacity and optimize the distribution of coal powder and combustion process. The reconstruction consisted of replacing the centrifugal separators with louvers in four of eight channels.

The results of measurements presented in [1-3] show that much better distribution of the pulverized coal is achieved for the louvers than for the centrifugal separator. The former gives 82.3% by 17.7% [2] for the main and secondary burners, respectively, the latter 56.2% by 43.8% for the position of the blades of about 20°. The distribution of the coal powder has a major influence on the combustion process. The gas mixture distribution for the main burners is also more regular for the louvers with 57%, compared to 49% for centrifugal separator. This improves the transport properties and the combustion process.

The fineness of pulverized coal is similar in both systems of separation. The residues on sieves  $R_{90}$  and  $R_{1000}$  are 65% and 6-9%, respectively. The rest of the coal powder on R1000 (for both configurations of separators) for secondary burners is below 4%. The effect of ventilation depends a little on the separation system and under normal conditions its value is about 200,000 m<sup>3</sup>/h.

The reconstructions resulted in 70:30% distribution of the coal powder and 60:40% of the gas mixture on the main and secondary burners, in accordance with the requirements of the supplier. The quality of milling was improved slightly, so that the residues on the sieves  $R_{90}$  and  $R_{1000}$  were 65-70% and below 10%, respectively. But the tests, performed after the reconstruction, have shown that the distribution 70:30% of the coal powder is not optimal and proper combustion was not able to be obtained. The possibility of additional reconstruction is considered.

#### Numerical methods

Today, numerical methods are an essential tool in engineering analysis and they are used in all branches of science and technology for flow simulations. There is a wide range of software for numerical simulations. Usage of such codes offers an important alternative to laboratory tests. It is especially useful when investigations on complex thermal power plants are needed [8-25].

Commercial ANSYS FLUENT software is based on the finite volume method. There are two approaches for the numerical simulation of the multiphase flow. They are known as Euler-Lagrange and Euler-Euler approach. In the first, the primary phase is treated as continuum by solving the time-averaged Navier-Stokes equations. The behavior of the dispersed phases is obtained by following a large number of the particles, through the calculated primary phase flow field. Particle trajectories are calculated in the given intervals during the primary phase flow calculations. Dispersed and primary phases can exchange mass, momentum, and energy. The basic assumption in this model is that the volume fraction of the dispersed, secondary phase is below 10-12%, although its mass can be even greater than the mass of the primary phase.

The different phases in the Euler-Euler approach are considered as interpenetrating continua, thus introducing phasic volume fractions as continuous functions of time and space. The sum for all phase's volume fractions in each computational cell is equal to one. Conservation laws are applied to each phase in order to obtain a set of equations that is similar for all phases. Constitutive relations obtained from empirical information must be added to close the set of equations.

In the Euler-Euler approach, there are three models of multiphase flow: the volume of fluid (VOF), the mixture model and the Eulerian model.

The VOF model is a surface-tracking method applied in cases where the position of the interface between two or more immiscible fluids is to be determined. A single set of momentum equations is shared by the fluids, while the volume fraction of each of the fluids is tracked in each computation cell of the numerical domain. This model can be applied for free-surface flows, stratified flows, filling, sloshing, *etc*.

The mixture model is a simplified multiphase model that can be used in modeling flows where the phases move at different velocities using the concept of slip velocities, but the existence of local equilibrium at small length scales is assumed. This model can include *n* phases, where the equations of continuity, momentum, and energy conservation are solved for the mixture, while the volume fraction equations are determined for each of the secondary phases. Algebraic equations are used in solving the relative velocities. This model enables selection of granular secondary phases and can be used as a good substitution for the full Eulerian multiphase model, in cases with wide size distribution of solid phase or when the interphase laws are unknown.

The full Eulerian model is the most complex of all models of multiphase flow in the used software. In this model the additional equations of mass and momentum conservation are solved for each phase separately. Any combination of liquid, gas and solid phases can be modeled. The Eulerian method of determining the flow field is used for both primary and secondary phases. Coupling between phases is included through the pressure and coefficient of interphase exchange depending on the types of phases involved. Thus, for the flow with solid fractions, the pressure and coefficient of intermediate exchange are obtained by kinetic theory. The number of secondary phases in the Eulerian model is limited either by memory requirements or convergence behavior providing sufficient memory.

The Lagrangian discrete phase model is based on the Euler-Lagrange approach where the fluid phase is treated as a continuum by solving the time-averaged Navier-Stokes equations, whereas the dispersed phase is solved by numerically integrating the equations of motion for the dispersed phase, *i. e.* computing the trajectories of a large number of particles or droplets through the calculated flow field. The dispersed phase consists of spherical particles that can exchange mass, momentum, and energy with the fluid phase. Although the continuous phase acts on the dispersed phase through drag and turbulence while *vice versa* can be neglected, the coupling between the discrete and continuous phase can be included. The discrete phase model is the only multiphase model where the particle distribution can be included.

#### Numerical flow simulation

The results of the numerical simulation were obtained using the mixture model in the Euler-Euler approach and the Lagrangian discrete phase model. In the mixture model the phases are allowed to be interpenetrating. The volume fractions in the control volume can have any value between 0 and 1. This model allows the phases to move with different velocities, using slip velocity between the phases.

The numerical modeling procedure of the multiphase flow in the ventilation mill and mixture channel is made up of two steps. The first step is geometry preparing and mesh generating. An unstructured tetrahedral grid consisted of 2996772 volume and 706444 surface elements is generated.

In the second step the flow field is calculated, after defining the general and multiphase model, phases and their interactions, viscous and turbulence model, boundary conditions, accuracy of numerical discretization, and initialization of the flow field. After obtaining solution convergence, post-processing and analysis of results were made.

The geometry of the model is faithful to the original design, except that the smallest details were omitted because of the limitation of the available memory. In figs. 2(a) and 2(b) the volume mesh is shown for mill with the louvers (a) and centrifugal separator (b).

The input data for the numerical simulations are based on the measurements conducted by the Department of Thermal Engineering and Energy, Vinča Institute, in 2008. Measurements performed on the mills 17 and mill 25 of blocks B1 and B2, are used for comparison, respectively. The input data used in the numerical simulations are given in tab. 1 [2].

The secondary phases in the numerical simulations are pulverized coal, sand and moisture. In the mixture model the pulverized coal is modeled as a mono-dispersed granular phase, with coal and sand particles diameters equal to 150  $\mu$ m and 300  $\mu$ m, respectively. The mono-dispersed coal powder was modeled because different diameters must be treated as different phases, but at the same time the number of phases was limited according to the computer resources. The particle weight and drag are accounted for. The restitution coefficients are chosen to be 0.9 for collisions between the particles of the



Figure 2. Volume mesh in the whole numerical domain for ventilation mill with louvers (a) and centrifugal separator (b)

0.9 for collisions between the particles of the granular phases. The k- $\varepsilon$  mixture turbulence model is used in modeling turbulence.

|  | Blinds  | Centrifugal separator   |
|--|---|---|
| Volume flow rate of recirculating gases  | $\dot{V}_{\rm sr} = 95.87 \text{ m}^3/\text{s}$   | $\dot{V}_{\rm sr} = 107.66 \text{ m}^3/\text{s}$  |
| Mass flow rate of coal                   | $\dot{m}_{\rm sr} = 16.72 \text{ kg/s}$   | $\dot{m}_{\rm sr} = 17.97 \ {\rm kg/s}$   |
| Moisture content in pulverized coal      | $W_{\rm p} = 5.68\%$  | $W_{\rm p} = 5.68\%$  |
| Mass flow rate of pulverized coal        | $\dot{m}_{\rm pulv.coal} = 7.28 \text{ kg/s}$   | $\dot{m}_{\rm pulv.coal} = 6.37 \text{ kg/s}$   |
| Volume fractions of the secondary phases | $\alpha_{\text{pulv.coal}} = 5.11 \cdot 10^{-5}$<br>$\alpha_{\text{sand}} = 1.67 \cdot 10^{-5}$<br>$\alpha_{\text{wat.vap.}} = 0.135$ | $\alpha_{\text{pulv.coal}} = 5.65 \cdot 10^{-5}$<br>$\alpha_{\text{sand}} = 1.81 \cdot 10^{-5}$<br>$\alpha_{\text{wat.vap.}} = 0.129$ |

 Table 1. The parameters used in numerical simulations

The standard no-slip boundary condition is applied at all walls including the mill impeller that rotates with 495 rpm. Its rotation is modeled with multiple reference frames (MRF) option in the software. The walls of the mixture channels are well insulated, so the adiabatic thermal boundary condition is applied. At all exits the value of static pressure is defined. The velocity is defined at the mill entry in such a way that volume flow rate of the recirculating gases be satisfied. The first order accurate numerical discretization is used, because the calculation with the second-order schemes is unstable.



Figure 3. Cross-sections of volume mesh at lower louvers and exit to lower burner (a) and around centrifugal separator (b)



Figure 4. Surface grid on several upper louvers (a) and on centrifugal separator (b)

In the analysis of the results it should be taken in account that the numerical simulations have some limitations. The first type of the constraint is related to the complexity of the physical models incorporated in the used software and possibility of obtaining relevant results. This especially holds for turbulence models, multiphase flows, and combustion models. In the real ventilation mill the coal is milled. However, the software ANSYS FLUENT 12 belongs to CFD codes in which the process of milling can not be modeled. Therefore, in the numerical simulation the solution is obtained as if the mixture of recirculating gases, pulverized coal, and sand entered the ventilation mill.

Another type of restriction is a very complex geometry which includes the mill impeller and housing, a large number of the densely placed louvers, as well as complex geometry of the centrifugal separator

In figs. 3(a) and 3(b) the cross-sections of the volume mesh at the lower louvers and exit to the lower burner (a) and around the centrifugal separator (b) are shown. The surface grid on the several upper louvers and the centrifugal separator can be seen in fig. 4(a) and 4(b).

## **Results of numerical simulation**

The results of the numerical simulations are presented quantitatively using tables and qualitatively by displaying fields of the velocity vectors and volume fractions of the granular phases. Also, the paths of the mixture and pulverized coal are shown. The results obtained using the mixture model of the Euler-Euler approach are given first. Thus, in tab. 2 the distribution of the gas mixture on the main and secondary burners for configurations with the louvers and centrifugal separator is given, while in tab. 3 the gas mixture velocity at each exit is presented.

|                      | Gas mixture distribution<br>(louvers) |                      | Gas mixture distribution<br>(centrifugal separator with blades at 20°) |                      |  |
|----------------------|---------------------------------------|----------------------|--|----------------------|--|
|                      | Measurements [2]                      | Numerical simulation | Measurements<br>[2]  | Numerical simulation |  |
| Main lower burner    | 29%                                   | 29.7%                | 25%  | 24.5%                |  |
| Main upper burner    | 28%                                   | 26.0%                | 24%  | 23.6%                |  |
| Second. lower burner | 20%                                   | 22.5%                | 27%  | 26.3%                |  |
| Second. upper burner | 23 %                                  | 21.8 %               | 24%  | 25.6%                |  |

### Table 2. Gas mixture distribution

| Table 3. | Velocity | of gas | mixture |
|----------|----------|--------|---------|
|----------|----------|--------|---------|

|                      | Velocity [ms <sup>-1</sup> ]<br>(louvers) |                      | Velocity [ms <sup>-1</sup> ]<br>(centrifugal separator with blades at 20°) |                      |  |
|----------------------|---|----------------------|--|----------------------|--|
|                      | Measurements [2]                          | Numerical simulation | Measurements [2]   | Numerical simulation |  |
| Main lower burner    | 29.1                                      | 31.0                 | 29.9   | 30.0                 |  |
| Main upper burner    | 27.4                                      | 21.3                 | 28.0   | 27.1                 |  |
| Second. lower burner | 18.3                                      | 22.4                 | 30.0   | 24.6                 |  |
| Second. upper burner | 21.4                                      | 22.0                 | 28.1   | 24.3                 |  |



Figure 5. Velocity of gas mixture in a vertical plane passing through rotation axis of mill; louvers (a), centrifugal separator (b)

Comparisons of the measurements and numerical simulations show good agreement as to the distribution of the gas mixture with differences up to 10% for both configurations. For separator with the louvers the gas mixture velocity is in very good agreement for the main lower burner and secondary upper burner, while for the main upper burner difference is about 28%. Better agreement of the measured and numerical results is obtained for the mill with the centrifugal separator where the largest difference at the secondary lower burner is about 22%.

The absolute velocity of the mixture in a vertical plane passing through the rotation axis of the mill with the louvers (a) and with centrifugal separator (b) is shown in fig. 5. The highest velocity of order 100 m/s occurs due to the rotation of the mill, while in the mixture channel velocity is up to 50 m/s. It is noticeable that there is a local increase in the velocity in the transition zones from the vertical to the horizontal ducts that directs the mixture toward the main and secondary burners. Also, there are the zones of very low velocity or even stagnation in front of the central body of the centrifugal separator.

In fig. 6 the mixture velocity vectors at the main lower burner and louvers (a), the main upper burner and louvers (b) and the centrifugal separator (c), can be seen. The

zones of separation where reversed flow occurs can be noticed, especially at the beginning of the horizontal ducts. For the louver separator the flow towards the lower main burner is rather smooth, fig. 6(a), opposite to the upper main burner, fig. 6(b), and the main burner for the centrifugal separator, fig. 6(c), so that some simple geometry modifications (similarly to the main lower burner) would make the mixture to flow more regularly at these places.

The path lines of the gas mixture are shown for the upper louvers, lower louvers and centrifugal separator in figs. 7(a)-7(c), respectively. It can be seen that the louvers change the direction of the gas mixture flow abruptly, so that the coal particles with larger inertia can not follow movement of the gas phase between the louvers. The vanes of the centrifugal separator only slightly modify the paths of the gas mixture, resulting in its almost equal distribution at all burners.

The distribution of the pulverized coal at the main and secondary burners for configurations with the louvers and centrifugal separator obtained by the mixture model is given in tab. 4. One of the limitations of the mixture model can be noticed from tab. 4, *i. e.* the same distribution of the pulverized coal and the gas mixture at the burners were obtained. The coal distribution for configuration with the centrifugal separator could be acceptable except

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for the secondary upper burner. On the other hand, for configuration with the louver separator there is a good agreement only for the main lower burner and pronounced discrepancy for other burners. Obviously, the mixture model coupled with such complex geometries can not give results, that are reliable enough. That is why the Lagrangian discrete phase model was employed next.



Figure 7. Path lines of mixture around louvers (a and b) and centrifugal separator with blades at 20° (c)

|                      | Pulverized coal distribution (louvers) |                      | Pulverized coal distribution<br>(centrifugal separator with<br>blades at 20°) |                      |
|----------------------|--|----------------------|---|----------------------|
|                      | Measurements<br>[2]                    | Numerical simulation | Measurements<br>[2]   | Numerical simulation |
| Main lower burner    | 30.8%                                  | 29.7%                | 30.4%   | 24.5%                |
| Main upper burner    | 51.5%                                  | 26.0%                | 25.8%   | 23.6%                |
| Second. lower burner | 8.5%                                   | 22.5%                | 30.7%   | 26.3%                |
| Second. upper burner | 9.2%                                   | 21.8%                | 13.1%   | 25.6%                |

In the Lagrangian particle tracking method instantaneous positions and velocities of the dispersed phase are solved from a set of ordinary differential equations that describe particles motion. The influence of the continuous phase was modeled by the dispersion of particles due to turbulence and drag. Weight of the particles was also accounted for in the simulation. The complete range of the coal particle sizes was divided into four groups, namely 0-90  $\mu$ m, 90-200  $\mu$ m, 200-500  $\mu$ m, and 500-1000  $\mu$ m. The particle size distribution was defined using the Rosin-Rammler equation based on the assumption that an exponential relationship exists between the particle diameter *d*, and the mass fraction of the particles with diameter greater than *d*:

$$Y_{d} = e^{-(d/d)^{n}} \tag{1}$$

where  $\overline{d}$  and *n* are the mean diameter and the spread parameter. The mass fractions were chosen according to the residue on sieves, so the mean diameter and the spread parameter of the Rosin-Rammler distribution function are 152 µm and 1.52, respectively. In tab. 5 the distribution of the pulverized coal at the main and secondary burners for configurations with the louvers and centrifugal separator obtained using discrete phase model is given.

|                      | Pulverized coal distribution (louvers) |                      | Pulverized coal distribution (centri-<br>fugal separator with blades at 20°) |                      |  |
|----------------------|--|----------------------|--|----------------------|--|
|                      | Measurements [2]                       | Numerical simulation | Measurements<br>[2]  | Numerical simulation |  |
| Main lower burner    | 30.8%                                  | 28.4%                | 30.4%  | 30.1%                |  |
| Main upper burner    | 51.5%                                  | 56.4 %               | 25.8%  | 26.3%                |  |
| Second. lower burner | 8.5%                                   | 6.9%                 | 30.7%  | 28.7%                |  |
| Second. upper burner | 9.2%                                   | 8.3%                 | 13.1%  | 14.9%                |  |

Table 5. Distribution of pulverized coal; discrete phase model

The distribution of the coal obtained by the Lagrangian particle tracking method compares rather well to the measurements, giving smaller differences for the centrifugal separator, due to its considerably less influence on the coal particles motion. Also, disagreement occurs because the precise distribution of the coal particle sizes after milling was not determined (only available data were residues on the sizes  $R_{90}$  and  $R_{1000}$ ), whereas the results of the numerical simulation strongly depend on the size distribution.

In figs. 8(a)-8(d) the paths of the pulverized coal in the vertical duct with the lower, upper louvers and centrifugal separator are shown. It is clear that both the lower and upper

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Figure 8. Paths of pulverized coal in the vertical channel for configuration with lower louvers (a), upper louvers (b), centrifugal separator with blade angle at  $20^{\circ}$  around centrifugal separator (c), and from centrifugal separator to the burners (d); particles traces are colored by particle diameter [m] (color image see on our web site)

louvers actually work as obstacles for most coal particles except for the smallest ones. Because of the narrow gaps between the louvers more than 82% of the coal powder is directed to the main burners. Distribution of the coal powder, for the centrifugal separator, at all burners with the exception of the secondary upper burner is almost equal. The centrifugal separator acts in a similar way on the motion of the coal particles and gas phase. From fig. 8d it can be noticed that coal particles of all sizes reach the secondary upper burner, but most of them are with the smallest diameter.

#### Conclusions

The results obtained by the numerical flow simulations in the ventilation mill EVT N 270.45 of Kostolac B power plant, clearly show that usage of CFD code provides all details of the flow field in the complex geometry plant. The numerical simulations are performed for two kinds of the separators in the mixture channel, *i. e.* the louvers and centrifugal separator.

The choice of the mixture model in the Euler-Euler approach of the multiphase flow was done according to the characteristics of the mixture, complexity of the geometry, memory requirements, and convergence behavior of the full multiphase model. The gas distribution and velocity of the gas mixture obtained by the mixture model is in accordance with the measurements at the main and secondary burners. The pulverized coal distribution at the main and secondary burners is not reliable enough due to the limitations of the mixture model.

Because of that the Euler-Lagrange approach of the multiphase flow was finally used. The distribution of the coal obtained by the Lagrangian particle tracking method agrees well with the measurements. The agreement is better for the centrifugal separator than the louver separator, because the influence of the former to the coal particles motion is considerably less. We have to point out that the results of the Lagrangian particle tracking method are mostly dependent on the distribution of the coal particle sizes after milling.

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