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CFD ANALYSIS OF THE INFLUENCE OF CENTRIFUGAL SEPARATOR GEOMETRY MODIFICATION ON THE PULVERIZED COAL DISTRIBUTION AT THE BURNERS

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Summary

This paper presents the results of 3D numerical flow simulation in the ventilation mill (VM) and air mixture channel (AMC) of Kostolac B power plant, where a centrifugal separator with adjustable blade angle is used. Numerical simulations of multiphase flow were performed using the Euler-Euler and the Euler-Lagrange approach of the ANSYS FLUENT software package. The geometry of the numerical model was almost identical to the VM and AMC of Kostolac B, except for the smallest details. An unstructured tetrahedral grid, consisted of almost three million cells, was generated. The main contribution of this paper is the original analysis of the influence of centrifugal separator (CFS) geometry modification on the coal powder distribution at the horizontal burners. The modification of the blade angle, blade shape, and vertical position of the separator and its effect on the coal powder distribution at the burners were analyzed and are published for the first time. Results of the numerical simulations were compared with the measurements and can be used in modifying the separator geometry and position to obtain optimal distribution of the pulverized coal at the burners. Application of these results, obtained by numerical methods, ensures significant savings in time and money, in the process of finding the optimal geometry of CFS.

Key words: *numerical flow simulation, ventilation mill, air mixture duct, centrifugal separator, pulverized coal distribution*

1. Introduction

Numerical methods are an important tool in engineering analysis, which are very often used for flow simulations as a useful alternative to measurements or to laboratory tests. They are frequently used for investigating the phenomena in complex industrial plants, such as power plants.

An appropriate distribution of coal powder at the main and secondary burners, together with its quality, are very important for regular and efficient combustion in the furnace as well as for the economic operation of a power plant. There are a lot of papers [1-4] studying the combustion process. Research conducted on the ventilation mill operation and on the impact of separators on the coal powder distribution at burners is very important for the optimization of thermal power plant exploitation. Modifications to the separator geometry and air mixing channel (AMC) contribute to more efficient power plant operation [5-11]. Very often, the influence of separator on the combustion process is studied experimentally in laboratory and by using numerical simulations [8,9]. Influence of the centrifugal separator (CFS) vertical position is analyzed in [12,13].

A detailed description of the VM and AMC with a louver separator and a CFS, used in the power plant Kostolac B, was given in [14-20]. Using a mixture model in the Euler-Euler approach of ANSYS FLUENT software package, an analysis of the multiphase flow in the AMC was performed for a CFS with blades at angles of 20^{o} and 30^{o} relative to the vertical axis. Results presented in [5,15] were in good agreement with the gas mixture distribution measurements at the burners. However, results obtained for the distribution of coal powder at the burners were not sufficiently highly accurate.

The mixture model is a simplified multiphase model that can be used in the modelling of flows by the Euler-Euler approach, as the most adequate of three possible varieties. The full Eulerian model is the most complex of all models of multiphase flow in the used software. In this model, additional equations of mass and momentum conservation are solved for each phase separately. Any combination of liquid, gas and solid phases can be modelled. The Eulerian method of determining the flow field is used for both primary and secondary phases. The number of secondary phases in the Eulerian model is limited either by memory requirements or the convergence behaviour 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 the vice versa may be neglected, the coupling between the discrete and the continuous phase can be included. The discrete phase model is the only multiphase model where the particle distribution can be included.

Due to a very complex geometry and a large number of grid cells, a convergent solution could not be obtained with the Eulerian model. In order to obtain more reliable distribution of coal powder at the burners in the AMC with a CFS of the Kostolac B power plant, the Lagrangian discrete phase model (DPM) that follows the Euler-Lagrange approach in ANSYS FLUENT is applied [8-12]. Transport equations are solved for the continuous phase while the motion of discrete second phase is simulated in a Lagrangian reference frame. The trajectories of discrete phase particles are computed in that way. The impact of the CFS blade angle on the coal powder distribution at the burners is obtained by performing numerical simulations for the blade angles of 20°, 30°, 40°, 50°, and 60° relative to the vertical axis. The influence of the blade profile curvature and the vertical position of the CFS are also analyzed using a curved blade and shifting the CFS upwards from the original position. This is original research which was carried out for the ventilation mill with a CFS.

Numerical methods are used in investigations of flow phenomena in many branches of science, engineering, complex industrial plants environmental protection, etc. Only small part of it is listed in the cited papers as an example [21-25].

2. Numerical modelling

The multiphase flow of recirculation gases and coal powder particles is analyzed. The solid phase is diluted and it participates in the composition of multiphase flow with a very small volume fraction, making the particle interaction and its influence on the gas phase negligible and implying the use of the DPM formulation in ANSYS FLUENT software package. Input data in the numerical model are defined on the basis of measurements performed on the selected mills. The data were explained in detail in [5,15,17-19].

It is assumed that a mixture of the hot recirculation gases, pulverized coal, and sand particles enters at the mill inlet. The volume flow rate of the gases is about 298,000 m^3/h, or 83 m^3/s, whereas the mass flow rate of the solid phases is of the order of 60 t/h, i.e. 16.7 kg/s. Volume fractions of coal and sand are $5.91 \cdot 10^{-5}$ and $1.93 \cdot 10^{-5}$, respectively, assuming (that) all particles are spherical in shape. It is considered that turbulence intensity at the inlet is of the order of 10%. The influence of turbulence is obtained through the k-ε turbulence model. Volume fractions of the secondary phases are very small, giving a dilute mixture. Sand particle diameter is taken to be 300μm. The standard no-slip boundary condition is applied to all walls including the mill impeller that rotates at 495 rpm. Its rotation is modelled with a multiple reference frames (MRF) option in the software. The adiabatic thermal boundary condition is applied. The value of static pressure is defined at all exits. The velocity is defined at the mill entry in such a way that the volume flow rate of recirculation gases be satisfied. The first order accurate numerical discretization is used because the calculation with the second-order schemes was unstable.

Mass distribution of coal powder at each burner is obtained as a main result of the simulation.

2.1 Size distribution of coal powder

In researching the influence of geometrical modifications on the distribution of coal powder at the burners, the Rosin-Rammler size distribution of particles at the entrance of ventilation mill is used. According to the analysis given in [6,15], the complete range of particle sizes from 0 to 1000 μm is divided into four size ranges. The mass fraction of coal powder in each diameter range is given in Table 1. The mean diameter and the spread parameter of the Rosin-Rammler distribution function are 152 μm and 1.5227, respectively.

Table 1 Mass fraction vs. size distribution of coal powder particles at the entrance of ventilation mill

Particle diameter range	Mass fraction in the range
(μm)	%
0 - 90	26
90 - 200	50
200 - 500	20
500 - 1000	4

2.2 Geometry and grid generation

Geometry of the ventilation mill and the AMC numerical model with a CFS, and a CFS alone with the blades at angles of 20°, 40°, and 60° relative to the vertical axis, are shown in Figures 1a to 1d. It was a challenge for the authors to create a numerical model of a complex ventilation mill in detail. In many papers, numerical simulations have been carried out for smaller objects or their models.

The blades of CFS are usually flat rectangular plates. In order to check the influence of the blade profile, a flat plate is cambered in such a way to give the same profile along the blade width. The maximum camber of 6% of the blade length is set at 30% from the leading edge. Figure 1e shows the geometry of the CFS with curved blades. Modification to the blade is chosen to be simple and applicable in exploitation. Because the width of the cambered and the flat blade is the same, it is examined whether the camber has any impact on the distribution of coal powder at the burners.

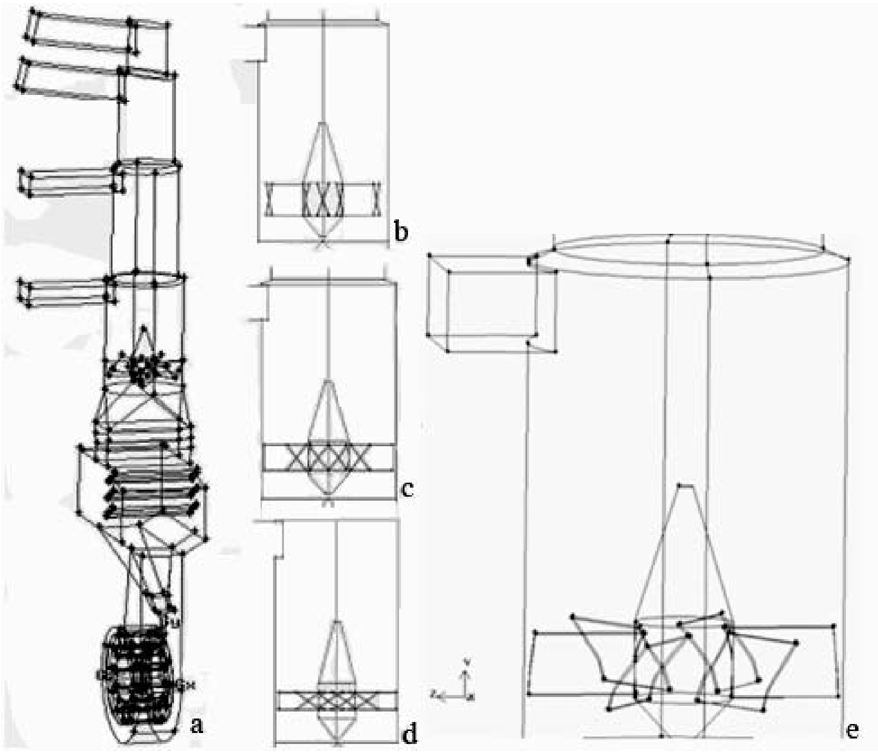


Fig. 1 Geometry of ventilation mill and AMC with different geometries of CFS

Because of the complexity of the realized ventilation mill and the AMC geometry, an unstructured mesh has to be generated in the numerical domain. In principle, a structured grid composed of a parallelepiped can be used in complex flows, but for a complex geometry with plenty of fine details, the only possible solution was an unstructured one. The structured grid may lead to undesirable oversimplifications of the geometry since it may be very difficult or impossible to deform the structure of the grid to fit the geometry.

Three grids were generated for the grid convergence study. After the study, the impact of an increasing number of meshes was determined and a compromise between calculation speeds, stability, and the accuracy of the model was made. The mesh is composed of 2 630 600 tetrahedral cells for the geometry with CFS blades set at 30° relative to the vertical axis. At approximately the same grid resolution, the change in the number of cells is below 1.5% for different CFS geometries. Note that the number of cells for the ventilation mill and the AMC with louvers is almost by one million larger for a similar grid resolution. The volume grids in the whole numerical domain and around the CFS can be seen in Figs 2a and 2c. The former figure relates to the blade at 50° and the latter to the one at 20°. Figures 2b and 2c present the surface meshes on the body and the CFS blades at 20° and 50°.

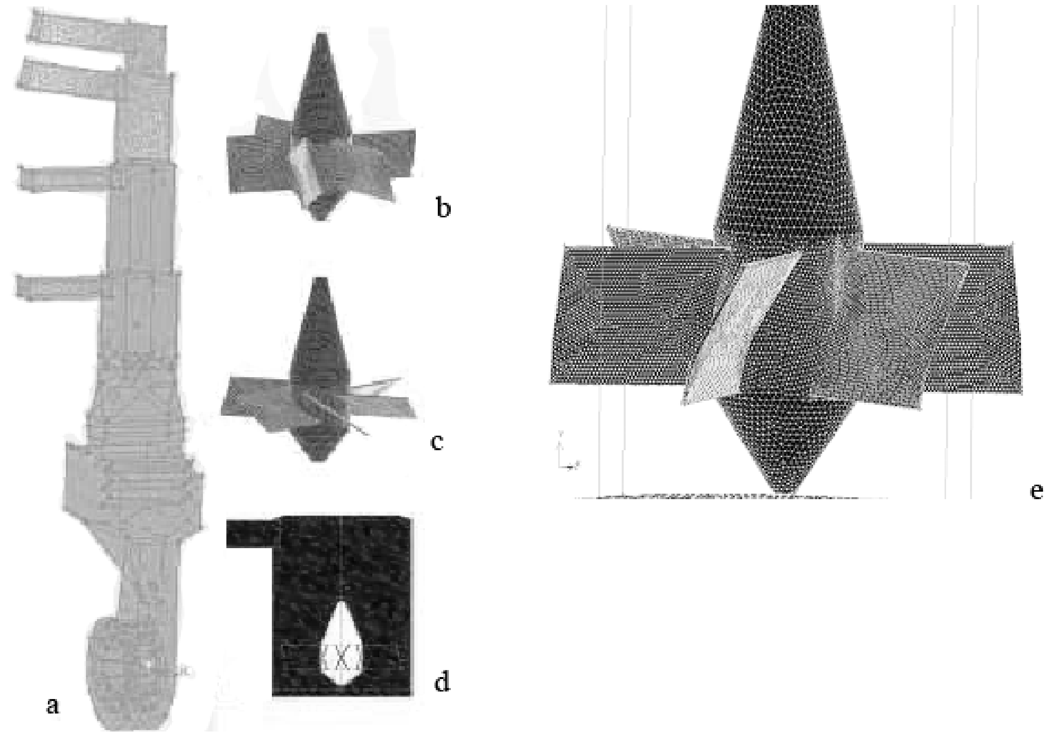


Fig. 2 Volume mesh for the VMAC with a CFS

3. Analysis of results and comparison with measurements

For the DPM method, while a discrete phase is injecting, boundary conditions are defined in a manner to include coal powder particles bounced from the solid boundary surface, i.e. the restitution in the normal and tangent directions to the solid surface. In this research, the same restitution boundary conditions were adopted as for the ventilation mill with louvers [6], meaning that the value of the bounced coefficient in the perpendicular direction is 1.0 and in the tangential 0.9. These values were chosen because the numerical particle size distribution of coal particles shows minimum deviation from the measurements.

Results of numerical simulation for the AMC, with a centrifugal separator, were compared with the measurement results from the reference [4]. Distribution of the coal powder at the burners for the VM and AMC with a centrifugal separator is presented in Table 2. No data were available for the distribution at the blade angle of 60° relative to the vertical axis. Under such a high angle of attack, the flow cross section is blocked significantly allowing the convergence of solution only for the continuous phase. When coal powder particles were injected into the continuous gas phase, their paths were incomplete for about 50% of particles, meaning that these particles do not move toward the burners but bounce between the CFS blades. Such a solution cannot be considered as a relevant one.

Table 2 presents the distributions of coal powder at each burner obtained by measurements for two mills (M17, M24) and by numerical simulations for different blade angles. According to the designer's recommendation, the blades of the realized CFS are set at an angle between 25° and 30°, resulting in almost equal distribution of the coal powder at the main burners and the secondary lower burner. This fact is confirmed by numerical simulations for a blade angle of up to 30°. Figure 3 shows the coal powder distribution at the burners as a function of the blade angle relative to the vertical axis. It can be noticed that the blade angle has a minor influence on the distribution at the main burners. On the other hand, it has a considerable impact on the distribution at the secondary burners. At a blade angle of 50°, the distribution of the coal powder at the secondary upper burner is even greater than at the main ones.

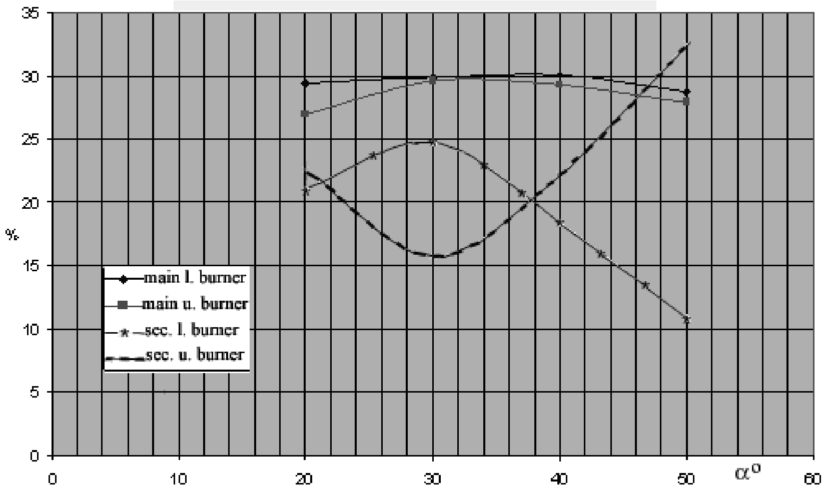
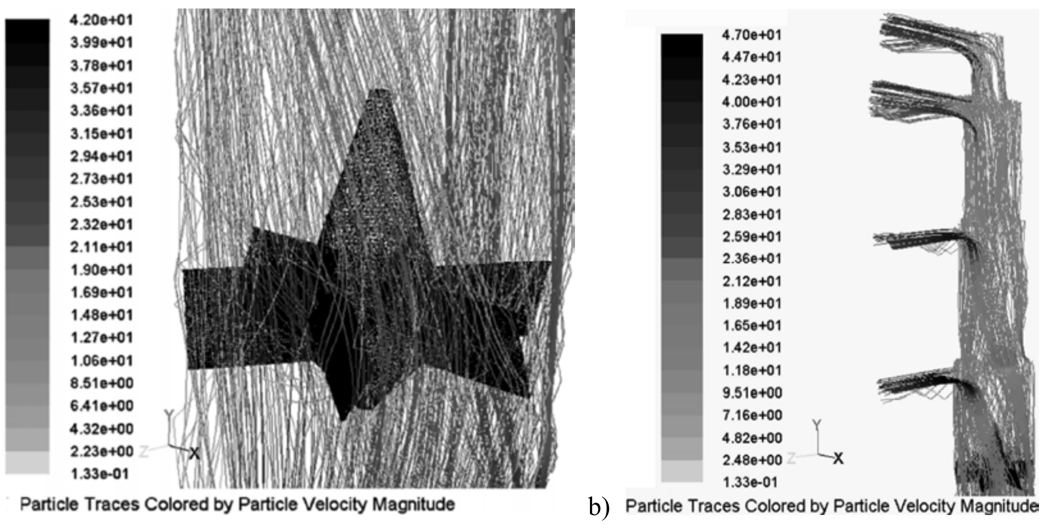


Fig. 3 Distribution of coal powder at the burners as a function of the blade angle

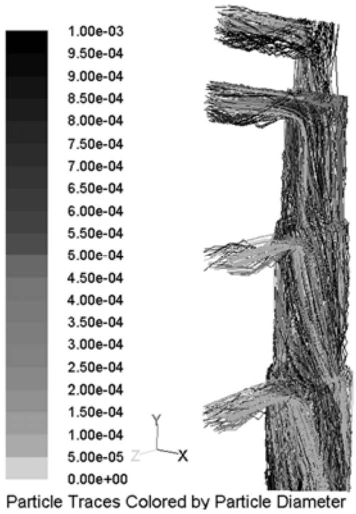
Table 2 The coal powder distribution (%) for different blade angles

	Experiments		Numerical simulation: DPM Mean diameter: d_{sr} = 152 μm Spread parameter: n=1.5227			
			blade angle			
	M17	M24	20°	30°	40°	50°
Main lower burner	**30.4**	**33.7**	**29.4**	**29.9**	**30.1**	**28.7**
Main upper burner	**25.8**	**28.2**	**26.9**	**29.6**	**29.3**	**27.9**
Secondary lower burner	**30.7**	**25.8**	**21.1**	**24.8**	**18.4**	**10.9**
Secondary upper burner	**13.1**	**12.3**	**22.6**	**15.7**	**22.2**	**32.5**

Part of the results obtained by numerical simulations for different blade angles can be seen in Figures 4 to 6, where paths of coal powder particles around the CFS and along the AMC are shown, coloured by the particle velocity and the size. Velocity vectors of the gas phase around the blades set at an angle of 50° point to the region of reverse flow. This occurs due to a large angle between the blade and the oncoming flow, Figure 6d.

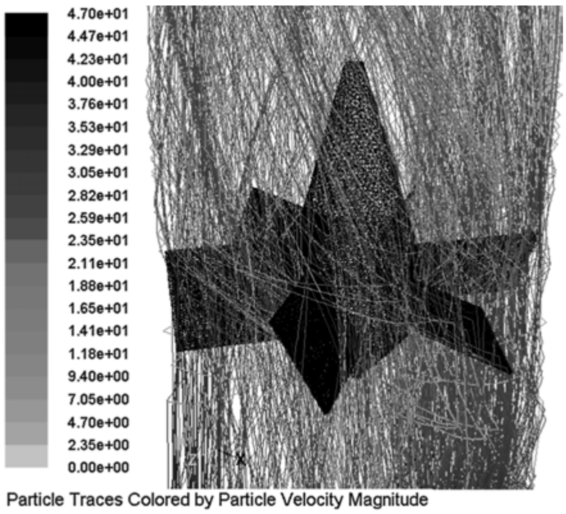


a) b)

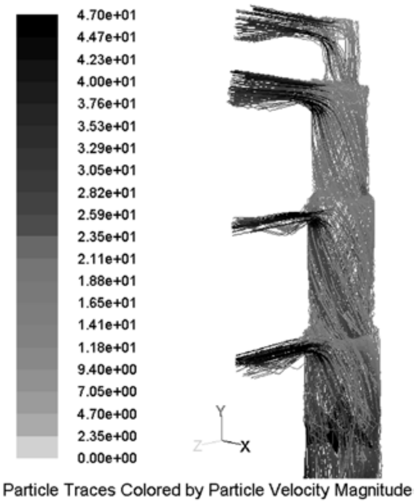


c)

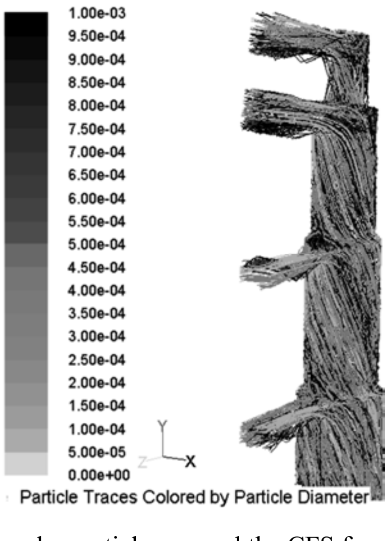
Fig. 4 Paths of coal powder particles around the CFS for a blade angle of 20°, coloured by particle velocity magnitude



a)



b)



c)

Fig. 5 Paths of coal powder particles around the CFS for a blade angle of 30°, coloured by particle velocity magnitude

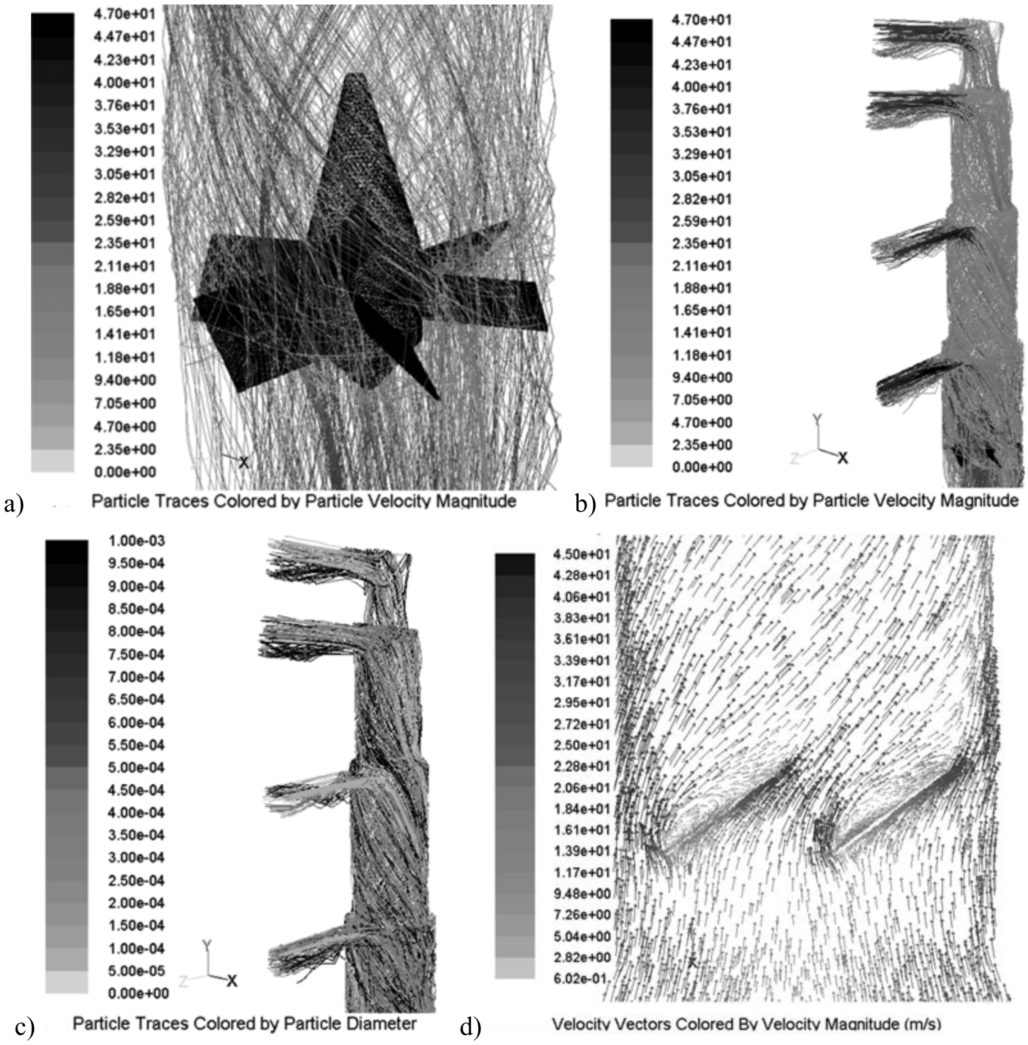


Fig. 6 Paths of coal powder particles around the CFS for a blade angle of 50^o, coloured by particle velocity magnitude

3.1 Influence of the blade shape

The coal powder distribution at the burners, obtained for flat and curved blades, is given in Table 3. It can be noticed that the tested blade curvature has a very small influence on the distribution of coal powder.

Table 3 Coal powder distribution (%) for different blade geometries

	Measurement (blade angle between 25° and 30°)		Numerical simulation: DPM model Mean diameter: d_{sr} = 152 µm Spread parameter: n=1.5227 Blade angle: 30°	
	M17	M24	Flat blade	Curved blade
Main lower burner	**30.4**	**33.7**	**29.9**	**31.1**
Main upper burner	**25.8**	**28.2**	**29.6**	**29.2**
Secondary lower burner	**30.7**	**25.8**	**24.8**	**24.1**
Secondary upper burner	**13.1**	**12.3**	**15.7**	**15.6**

Figure 7 shows the paths of coal powder particles near the CFS, whereas, Figure 8 the velocity vectors of gas phase around the body and the curved blades of the CFS.

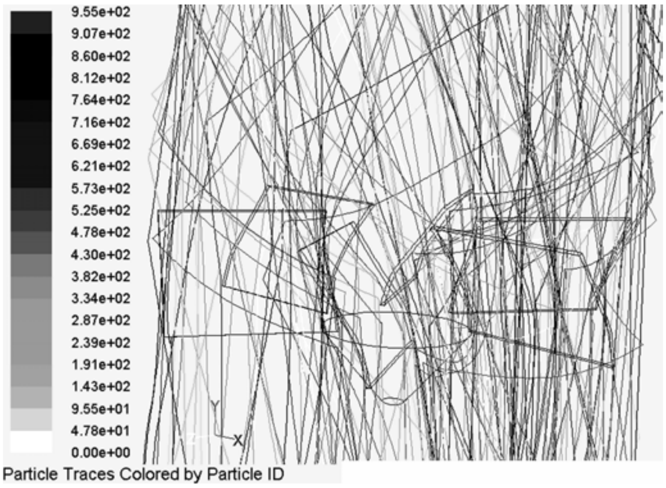
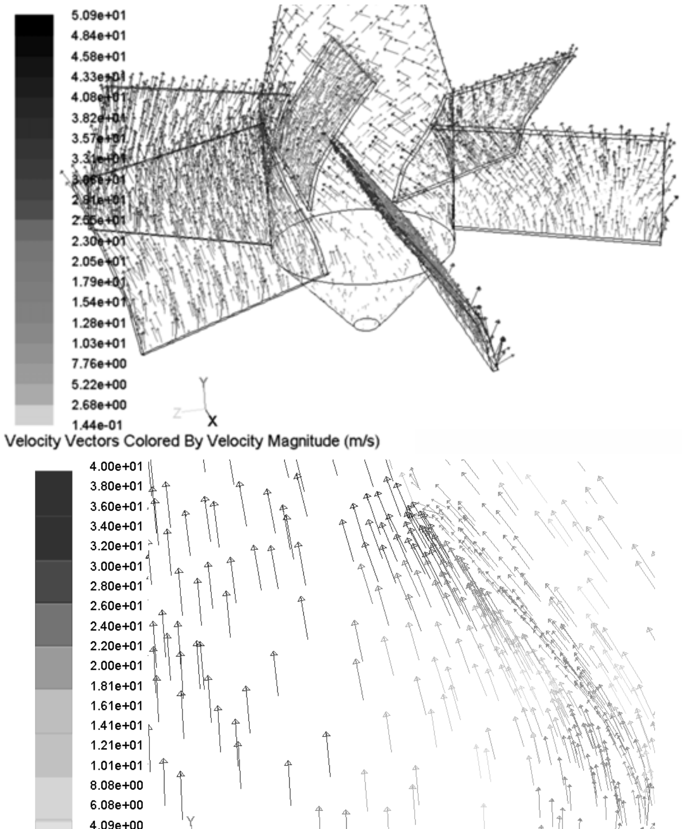


Fig. 7 Paths of coal powder particles near the CFS with curved blades

a)



b)

Fig. 8 Velocity vectors of the gas phase around the body and the curved blades of the CFS

3.2 Influence of CFS vertical position

In addition to the blade shape, the impact of vertical position of the CFS on the coal powder distribution at the burners is also analysed. In the performed numerical simulations, the CFS is shifted upwards by 0.5m and 0.7 m relative to the realized geometry. Flat blades set at an angle of 30° are used. In Table 4 gives the distribution of coal powder obtained by simulations. For both positions, the paths of coal powder particles (as a function of the velocity and the particle size) around the CFS and inside the vertical and the horizontal duct toward the main lower burner are shown in Figures 9a-9c.

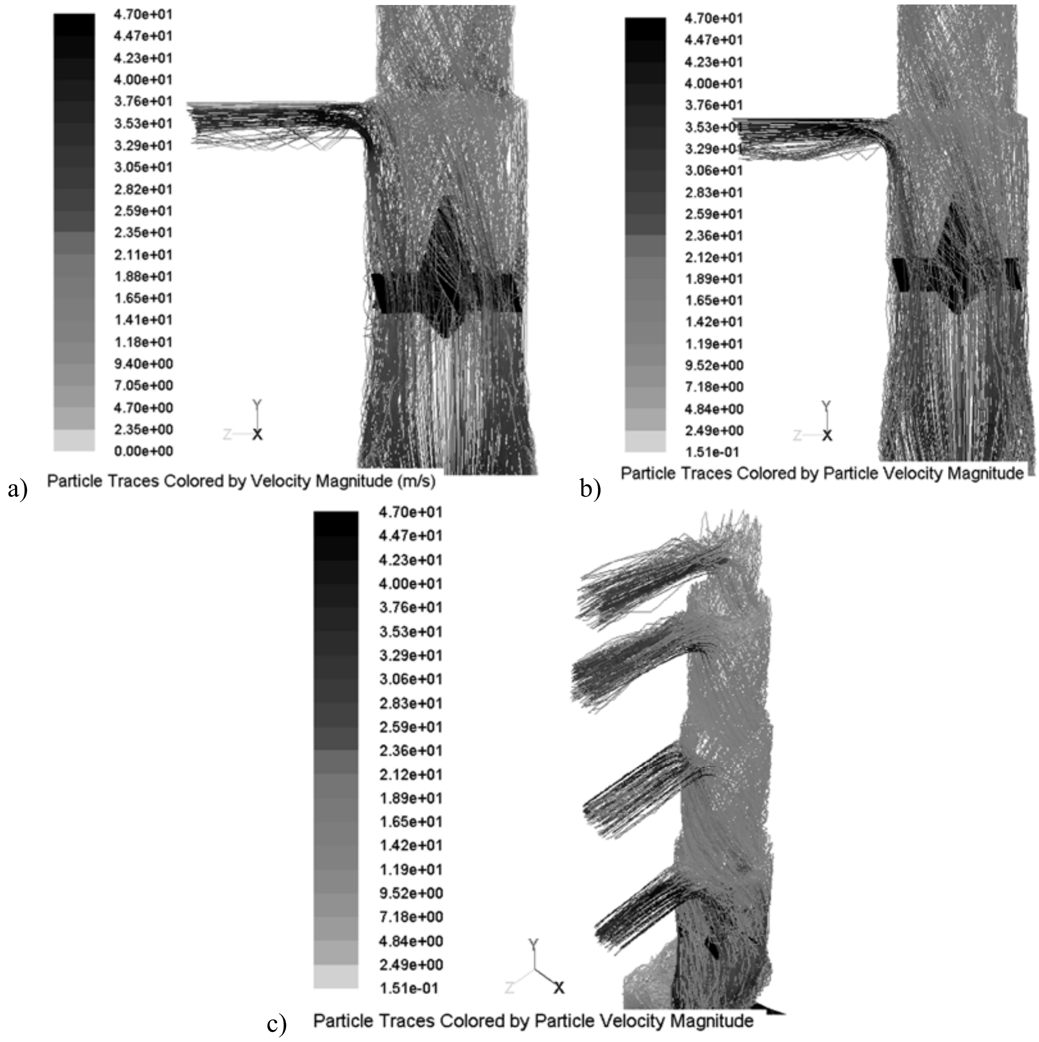


Fig. 9 Paths of coal powder particles for the CFS shifted upwards by 0.5 m (a), 0.7 m (b and c)

Figure 10 shows a diagram of coal powder distribution at the burners as a function of the CFS shift. The shift of the CFS by 0.5 m leads to maximum changes in the distribution that are slightly over 20% compared with the original geometry. However, for the CFS shift of 0.7 m, the changes are considerable for the main upper burner and secondary upper one. In this case, the distribution at the secondary burners is of the same order as for the main upper burner.

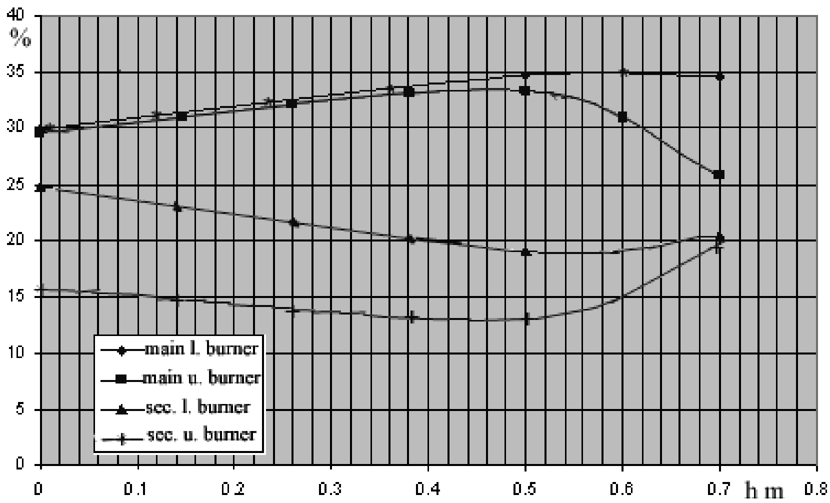


Fig. 10 Distribution of coal powder at the burners as a function of the CFS shifted upwards

Table 4 The coal powder distribution (%) for different vertical positions of CFS

	Measurement (angle of attack from 25° to 30°)		Numerical simulation: DPM model Mean diameter: $d_{sr} = 152$ μm Spread parameter: n=1.5227; Blade angle: 30°		
	M17	M24	Original geometry	CFS shifted upwards by 0.5 m	CFS shifted upwards by 0.7 m
Main lower burner	**30.4**	**33.7**	**29.9**	**34.6**	**34.5**
Main upper burner	**25.8**	**28.2**	**29.6**	**33.3**	**25.7**
Secondary lower burner	**30.7**	**25.8**	**24.8**	**19.1**	**20.4**
Secondary upper burner	**13.1**	**12.3**	**15.7**	**13.0**	**19.4**

4. Conclusions

Numerical results are obtained for a multiphase flow in the VM and AMC with a CFS, using a DPM and compared with measurements performed on the mills M17 and M24. The CFS blade is set at angles of 20°, 30°, 40°, 50° and 60° relative to the vertical axis. The influence of the blade angle on the coal powder distribution at the burners is analysed. It is noticed that about 50% of particle paths are incomplete for a blade angle of 60° and this result is rejected as irrelevant. The change in the blade angle affects only slightly the distribution at the main burners, while the impact on the secondary burners is substantial. At a blade angle of 50°, the share of the coal powder at the secondary upper burner is even larger than at the main burners.

In addition to the blade angle, the influence of the blade shape is considered using a curved blade. The blade is profiled with a maximum camber of 6% of the blade length set at 30% from the leading edge. The curved blade gives practically the same distribution of coal powder at the burners as the flat blade. Therefore, in the future, research will not consider the curvature of the CFS blades. Some assumptions are made in these numerical simulations. Evaluation of how they affect the results should be made in a future study.

Finally, the impact of the CFS vertical shift on the coal powder distribution at the burners is investigated setting the CFS by 0.5 m and 0.7 m upwards relative to the original position. For a shift of 0.5 m, distribution is changed by up to 20% compared with the original geometry, while that of 0.7 m results in a considerable increase at the secondary upper burner.

The next step in our research will be the modification of the existing CFS and its installation in the ventilation mill of Kostolac B thermal plant in order to test it in real conditions. The authors state that research results and optimizations can be used elsewhere in thermal power plants with a CFS.

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REFERENCES

[1] Tucakovic D., et al., A computer code for the prediction of mill gases and hot air distribution between burners' sections at the utility boiler, *Applied Thermal Engineering*, 28, (2008), pp.2178–2186

[2] Belosevic S., et al, A numerical study of a utility boiler tangentially-fired furnace under different operating conditions, *Fuel*, 87, (2008), pp.3331–3338

[3] Liming Y., Smith A. C., Numerical study on effects of coal properties on spontaneous heating in longwall gob areas, *Fuel*, 87, (2008) pp.3409–3419

[4] Živković N. V.,et al. Numerical Analysis of the Flue Gas-Coal Particles mixture flow in burner's distribution channels with regulation shutters at the TPP Nikola Tesla utility boiler, *Thermal science*:14 (2010), 2, pp. 505-520

[5] Kozic M.S., et al, Numerical simulation of multiphase flow in ventilation mill and channel with louvers and centrifugal separator, *Thermal Science*, 15, (2011),3, pp.677-689

[6] Kozic M., Ristic S., Katavic B., Puharic M, Analiza uticaja postavnog ugla lopatica centrifugalnog separatora na raspodelu ugljenog praha metodom DPM, Elaborat, Institut Goša, 2012

[7] Živković G.,et al., Numerical simulation of the influence of stationary louver and coal particle size on distri–bution of pulverized coal to the feed ducts of a power plant burner, *Thermal Science,* 13, (2009), 4, pp.79– 90

[8] Benim A.C., Stegelitz P., Epple B., Simulation of the two-phase flow in a laboratory coal pulveriser, Forsch Ingenieurwes (2005) 69: 197–204, DOI 10.1007/s10010-005-0002-4

[9] Shukla S.K., Shukla P., Ghosh P., Evaluation of numerical schemes for dispersed phase modeling of cyclone separators, *Engineering Application of Computational Fluid Mechanics*, l.5, (2011), 2, pp.235-246

[10] Kozic M., et al, Redesign of impact plates of ventilation mill based on 3D numerical simulation of multiphase flow around grinding wheel, *Fuel Processing Technology*, DOI: 10.1016/j.fuproc.2012.09.027.

[11] Ivanović V., et al, Reconstruction of the aero-mixture channels of the pulverized coal plant of the 100MW power plant unit, *Thermal Science*, 15, (2011), 3, pp.663-676

[12] Jianping J.,et al., Study of the influence of vane angle on flow, gas species, temperature, and char burn out in a 200 MWe lignite-fired boiler, *Fuel,* 89, (2010), pp.1973–1984

[13] Park H.Yet al, Coupled fluid dynamics and whole plant simulation of coal combustion in a tangentially-fired boiler, *Fuel* 89 (2010) pp.2001–2010

[14] B.Perković, et al, "Rekonstrukcije, modrnizacije i ostvarenje projektovane snage bloka B2 u TE Kostolac", *Termotehnika* 30, (2004),1, pp. 57-81

[15] Katavić B.,et al., Numerička simulacija strujanja u ventilacionom mlinu termolektrane Kostolac B - konfiguracija sa centrifugalnim separatorom, Institut Goša, 2010.

[16] Termotehnička ispitivanja i analiza rada kotlovskih postrojenja blokova B1 i B2 u TE Kostolac (2007, 2008 godina), PD TENT d.o.o., Proizvodno-tehnički sektor .

[17] Kozic M., Ristic S., Katavic B., Puharic M., Numerical simulation of multiphase flow around grinding wheel impact plates of ventilation mill, *Proceedings of III International Symposium Contemporary Problems of Fluid Mechanics*, May 12-13th, 2011, University of Belgrade, Faculty of Mechanical Engineering, Serbia

[18] Kozic M.,et al., Numerical Visualization of Multiphase Flow in Ventilation Mill and Mixture Channel, *Proceedings,* The 8th Pacific on Flow Visualization and Image Processing, Moscow, 21.-25.august 2011., Edt. Prof. DrI.A.Znamenskaya, MSU, Moskow, Russia, ISBN 978-5-8279-0093-1

[19] Kozic M., et al, Comparison of Numerical and Experimental Results for Multiphase Flow in Duct System of Thermal Power Plant, *Scientific Technical Review*, 60, (2010), 3-4, pp.39-47

[20] Feng R.,et al., Influence of the adjustable vane position on the flow and combustion characteristics of a down-fired pulverized-coal 300 MWe utility boiler, *Fuel Processing Technology*, 89 (2008), pp.1297–1305

[21] Margot, X., et al., "Numerical Modelling of Cavitation: Validation and Parametric Studies," *Engineering Applications of Computational Fluid Mechanics*, 6(1), 2012, 15-24

[22] Mahmoud, H., et al., "Numerical Analysis of Recirculation Bubble Sizes of Turbulent Co-Flowing Jet," *Engineering Applications of Computational Fluid Mechanics*, 6 (1), 2012, 58-73

[23] Chau, K.W., et al., "A three-dimensional pollutant transport model in orthogonal curvilinear and sigma coor–dinate system for Pearl river estuary," *InternationalJournal of Environment and Pollution*, 21(2), 2004, 188-198

[24] Wu, C.L., et al., "Mathematical model of water quality rehabilitation with rainwater utilization – a case study at Haigang," *International Journal of Environment and Pollution*, Vol. 28, No. 3-4, 2006, pp. 534-545

[25] Chau, K.W. ,et al., "3D numerical model for Pearl River estuary," *Journal of Hydraulic Engineering, ASCE*, 127(1), 2001, 72-82

[26] M. Kozić, S. Ristić, S. Polić-Radovanović, M. Puharić, Comparative analysis of wind direction impact on the air pollution in the region of thermal power plant Kostolac B by CFD, Ecologica, 19 (2012) broj 68, pp.563-570

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