3-D NUMERICAL SIMULATION OF MULTIPHASE FLOW DURING SEPARATION PROCESS OF COAL POWDER IN MILL INERTIAL SEPARATOR

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ABSTRACT

This paper presents the results of CFD simulation of multiphase flow within inertial separator in ventilation mill N. 400.42 of „TENT B2“ thermal power plant. Obtained results impersonate the influence of lower flaps positions within the separator on fineness of coal powder grinding on the exit of mill separator.

According to the real size model, 3D geometry with high rate of resemblance has been made. Taking in consideration number of cells, convergence time period and accuracy of the obtained solutions, appropriate numerical grid has been performed and used in simulations. Standard **k-ε** model for solving the gas phase turbulent model is used. Modeling of monodisperse coal particles flow within the gas phase is performed by use of integrated Lagrangian **DPM** (**D**iscrete **P**hase **M**odel) method. The measurements obtained on real time scale model are used in purpose of setting the boundary conditions in case of horizontal position of the lower regulation flaps - S13. Afterwards, simulations with setting the flaps in 3 new/different positions have been performed.

Results show the influence of the lower regulation flaps positions on the coal powder distribution and residual of coal particles on particular sieves on the outflow surface of inertial separator. The trends of inflection of these parameters can be considered in purpose of achieving optimum regulation of the mill and steam boiler operation.

Keywords: mill inertial separator, multiphase flow, coal powder, numerical simulation, steam boiler

1. Introduction

As the world energy consumption constantly grow, there is a permanent need for increasing capacities of the existing and building new energy production plants worldwide. Regarding the coal total consumption in Europe and Asia, slight grow in period of 2008 to 2012 is observable [1]. Therefore, revelation of the means for increasing energy efficiency of the coal consumption facilities is of great importance.

Analising the heat losses of large steam boilers, it can be considered that total heat loss corresponds in major to the wasted heat in flue gases (q_2) and noncombustible solid fuel (q_4) [2]. Heat losses in noncombustible solid fuel mostly depend on finesses of grinding of the solid fuel particles introduced to the burners of the steam boiler furnace. Operation of mill with position of the flaps in mill inertial separator has a great impact on assortment of the coal powder introduced to the air mixture classifier in duct after separator. Because of the complexity of the multiphase flow, it is purposeful to examine the characteristics of two-components flow in inertial separator for different positions of the regulation flaps with dimensions range of the coal particles, in order of optimization of mill and separator operation and regulation of the coal powder assortment by use of the obtained results.

In this paper, results of numerical simulations of multiphase flow within inertial separator for various positions of the lower regulation flaps are presented. 3D model of inertial separator is made on the basis of full scale facility integrated in coal preparation system at thermal power plant „Nikola Tesla - B2“. Detailed description of generated numerical grid is provided. Applied boundary conditions used in simulations represent measurements performed on full scale facility at reference/horizontal flaps position within the separator [3]. Simulations have been performed until the agreement on the measured values is achieved. Afterwards, the flaps are rotated for -10°, +10°, and +20° according to mathematical positive rotation direction. Coal particles, used in simulations, are spherical with diameters $d_s =$ (4000 , 2000, 1500, 1000, 500, 200, 90, 50) μm. Particular sieve residuals of coal particles on the exit of the separator and return channel have been considered.

For numerical simulation a commercial software pack ANSYS FLUENT has been used. Gas phase solutions are obtained by appliance of Oiler approach, while the momentum of particles is determined by use Lagrangain approach.

Taking in matter economical reliability and simplicity of use, it is considerable that there are numerous facts that give great importance to the computer numerical simulations and their use in solving complex problems of multiphase fluid flow dynamics. At present, it is commonly accepted that numerical simulations are unavoidable step in examining the fluid dynamics problems for large facilities in exploitation, especially if multiphase flow is considered, where there are difficulties in measuring velocity magnitude of solid particles.

2. Mathematical model

High complexity of used mathematical model refers to the internal processes of mass, momentum and energy transfer that occurs between solid particles and gas phase according to applied boundary conditions in multiphase flow. Mutual collision of the particles, particles impact on boundary frame, mass diffusion – mass reduction of the particles (evaporation process on surface of the solid particles in motion) and attended chemical reactions increase the rate of mathematical model complexity, by making it impossible to solve without performing numerical simulations.

In this case, Oiler-Lagrange approach is used. Gas phase is treated as continuum. Thus, for solving fluid flow time – averaged Navier – Stokes equations are applied. Coal particles are treated as solid objects [4]. Results of particles pathways and velocity magnitudes are obtained by use of standard momentum equation of solid body counting in a influence of results of surrounding conditions obtained in previous simulations of gas phase. **DPM** (**D**iscrete **P**hase **M**odel) model, integrated in ANSYS FLUENT software pack, allows such approach.

In order to simplify mathematical model for describing gas phase, following assumptions has been adopted:

- flow is turbulent and incompressible;
- flow is isothermal;
- flow is steady and three-dimensional;
- flow is chemically inert.

Following assumptions, for defining solid phase mathematical model, are applied:

- different size particle momentum has been considered;
- particles do not change mass by passing through the inertial separator;
- according to the isothermal flow of gas phase, constant temperature of the solid phase is maintained;
- during the impacts of the solid phase on separator's walls, according to the solid particles approach angle particles lose certain level of kinetic energy;
- the effects of internal particles collision is ignored;
- particles do not influence flow of the gas phase;
- particles have constant density.

Real turbulent multiphase flow characterizes chaotic, stochastic, 3-dimensional, unsteady movement of fluid particles. Transport of mass, momentum and exchange of energy between fluid particles can be described with general equation of conservation (Reynolds equation):

$$\frac{\partial}{\partial t}(\rho \Phi) + U_j \frac{\partial}{\partial x_j}(\rho \Phi) - \frac{\partial}{\partial x_j}\left(\Gamma_{\Phi} \frac{\partial \Phi}{\partial x_j} \right) = S_{\Phi} \; ; \tag{1}$$

where:

Φ - universal parameter of the gas phase (for instance: velocity gas components),

ρ - gas phase density,

U_j - components of gas phase velocity vector,

Γ_{Φ} - transport diffusion coefficient parameter of parameter Φ (for instance: if Φ represents components of gas phase velocity vector, then $\Gamma_{\Phi} = \mu$ – gas dynamic viscosity) and

S_{Φ} - the source (or sink – negative source) parameter of parameter Φ (for instance: if Φ includes components of gas phase velocity vector, then $S_{\Phi} = \partial P / \partial x_i$, gradient of surface forces exerted upon fluid particles).

In order to provide high values of efficiency rates, facilities, in which fluid flow with upper values of temperature is expected, are well insulated. Although, the difference between gas phase temperature and ambient temperature can be more then 200 K, outside surface temperature of ventilation mill and mill separator are quite close to the ambient temperature. Thus, the heat flux through the walls of the inertial separator can be ignored. This substantiates the assumption that gas phase fluid flow can be considered as isotherm flow. As temperature of gas phase is constant, solving the mass and momentum conservation equation is sufficient for determining the fluid flow. Consequently, density of the gas phase is constant in entire fluid flow volume and effects of lift movement can be ignored.
With applying the assumptions:

$$\frac{\partial}{\partial t} = 0 \; ; \tag{2}$$

$$\frac{\partial T}{\partial x_i} = 0 \;\; \Rightarrow \;\; \frac{\partial \rho}{\partial x_i} = 0 \; ; \tag{3}$$

mass and momentum conservation equation (Reynolds turbulent equation) take the following form:

$$\frac{\partial U}{\partial x_j} = 0 \; ; \tag{4}$$

$$U_j \frac{\partial U_i}{\partial x_j} - \frac{\partial}{\partial x_j}\left(\nu_{ef} \frac{\partial U_i}{\partial x_j} \right) = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} \; ; \tag{5}$$

$$\nu_{ef} = \nu + \nu_T \; ; \tag{6}$$

In the equations, the meaning of the used tags are:

U_i - averaged components of gas phase velocity vector,

x_i - spatial generalized coordinates,

P - averaged gas phase vector,

ν_{ef} - effective kinematic viscosity,

ν - molecular kinematic viscosity and

ν_T - turbulent kinematic viscosity.

According to the used turbulence model, turbulent kinematic viscosity is determined. Turbulent model, frequently used in numerical simulations, is two-equation **k-ε** model where:

k - turbulence kinetic energy $\left[k = 0.5\,\overline{u_i u_i} = 0.5\,(\overline{u_1 u_1} + \overline{u_2 u_2} + \overline{u_3 u_3})\right]$ and
ε - kinetic energy dissipation rate.

With additional transformation of differential equations (4) i (5), two-equation **k-ε** system is obtained which is numerically solved by use of finite volume method.

According to the Lagrangian approach for solving the solid phase momentum, essential momentum equation for solid body is used. Concept involves tracking off every single particle, with determining the pathways and velocity magnitudes. Previously mentioned assumptions are taken into account.

Following equation is used for determining position of the particles in fluid flow volume:

$$\frac{\mathrm{d}}{\mathrm{dt}}\left(\mathbf{x}_\mathrm{p}\right) = \mathbf{U}_\mathrm{P}\ ; \tag{7}$$

Vector position of the solid particle is tagged with $\mathbf{x}_\mathrm{p}$ and $\mathbf{U}_\mathrm{P}$ is the velocity vector of the tracked particles. According to the forces that are exerted upon coal particle, modified momentum equation is used for determining the velocity vector $\mathbf{U}_\mathrm{P}$:

$$\mathrm{m}_\mathrm{p}\frac{\mathrm{d}}{\mathrm{dt}}(\mathbf{U}_\mathbf{P}) = \Re_\mathrm{P}(\mathbf{U} - \mathbf{U}_\mathbf{P}) + \mathrm{m}_\mathrm{p}\mathrm{b}\mathbf{g} - \mathrm{V}_\mathrm{P}\nabla\mathrm{P}\ ; \tag{8}$$

where:

m_p - mass of the tracked particle,
$\mathbf{U}$ - instantaneous velocity vector of gas phase (sum of averaged velocity magnitude $\left(\mathbf{U}_\mathrm{C}\right)$ and its fluctuation $\left(\mathbf{u}_\mathrm{C}\right)$, previously determined in gas phase momentum equation by use of Oiler approach),
$\Re_\mathrm{P}$ - resistance function,
$\mathbf{g}$ - effective kinematic viscosity,
V_P - molecular kinematic viscosity and
$\nabla\mathrm{P}$ - turbulent kinematic viscosity.

The three members, from left to right, on the right side of the equals sign represent: resistance force to the solid particles movement through gas phase, force of gravity and buoyancy force of solid particles. Particle resistance function is calculated by following equation:

$$\Re_\mathrm{P} = 0.5\rho\mathrm{A}_\mathrm{P}\mathrm{C}_\mathrm{D}\left|\mathbf{U} - \mathbf{U}_\mathbf{P}\right|\ ; \tag{9}$$

where:

A_P - the cross section surface of the considered particle
C_D - drag coefficient of spherical particles, calculated by the following equation:

$$\mathrm{C}_\mathrm{D} = \frac{24}{\mathrm{Re}}\left(1 + 0.15\,\mathrm{Re}^{0.687}\right) + \frac{0.42}{1 + 4.25\times10^{4}\,\mathrm{Re}^{-1.16}}\ ; \tag{10}$$

Tag Re in the equation stands for Reynolds number for solid particles. Exposed equation for calculation of drag coefficient is valid for spherical particles for which $Re < 10^5$.

3. Numerical model

Real scale facility is used for modeling 3D geometry. Modeling has been performed with minor deviations to the real scale facility, without neglecting crucial details and shapes which would cause great deformations of multiphase velocity vectors. Geometry used in performing 3D model is shown in Figure 1.

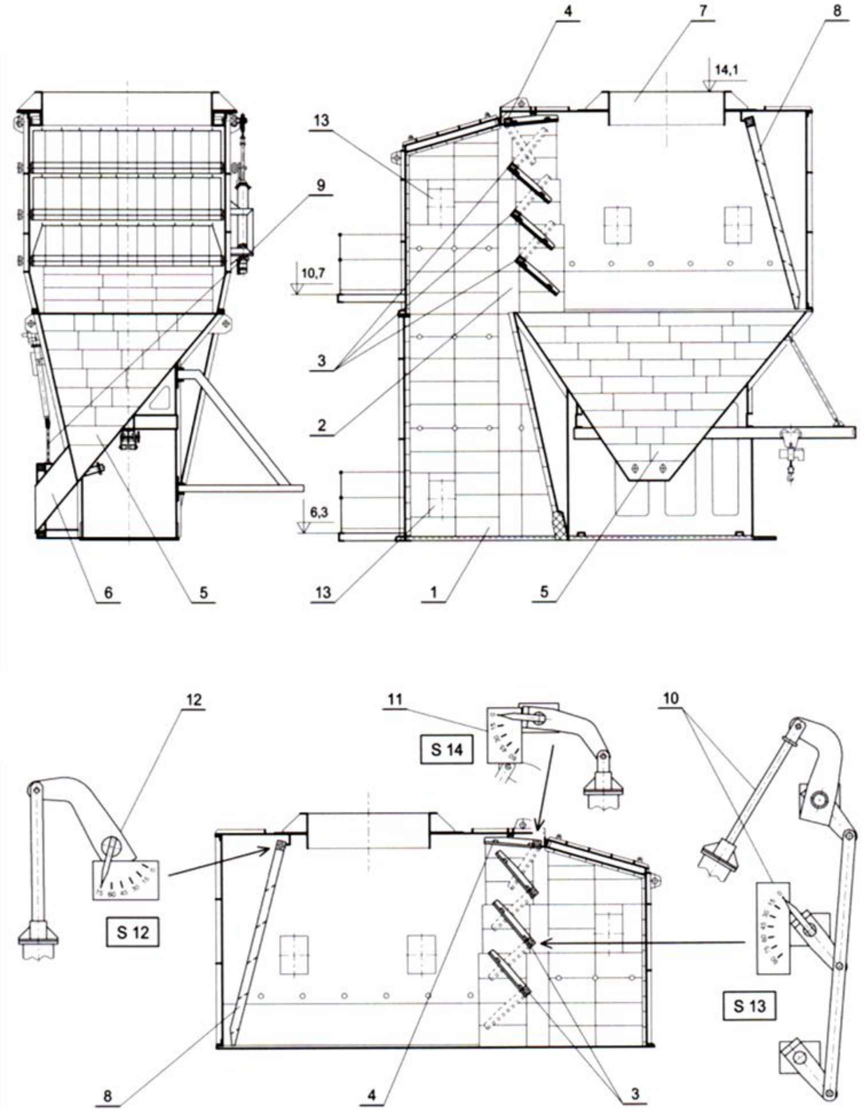


Figure positions:

1) Separator inlet; 2) Horizontal section of the separator; 3) Lower regulation flaps – S 13; 4) Upper flap – S 14; 5) Separator hopper; 6) By-pass channel; 7) Separator outlet; 8) Additional back-flap – S 12; 9) By-pass channel flange; 10) Lower regulation flaps rotating mechanism; 11) Upper flap rotating mechanism; 12) Additional back-flap rotating mechanism; 13) Maintenance aperature.

Figure 1. Cross view of the interior of the inertial separator

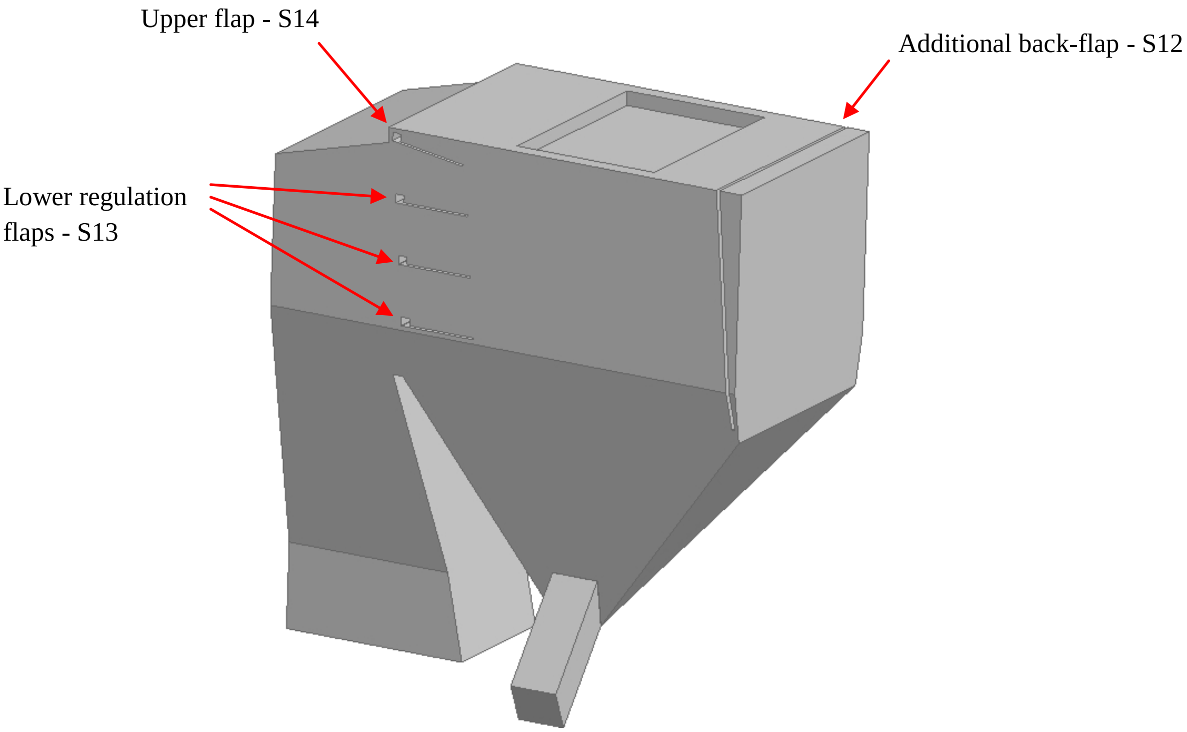


Figure 2. 3D model of inertial mill separator with displayed allocation of the flaps

Before generating numerical grid, inlet and outlet surfaces are defined. Regarding the differences between velocity vectors of solid particles of different size on the outlet of the ventilation mill chamber, uniformity of distribution of the particles on the inlet surface of inertial separator is not applicable. Thus, inlet is divided in four equal surfaces. Various allocation of the solid particles of the different size is applied on every inlet surface. Surface that introduce gas phase with solid particles to the classifier is marked with outlet. Outlet1 is used for outlet surface that introduce larger solid particles, through recirculation channel, to the ventilation mill for re-milling.

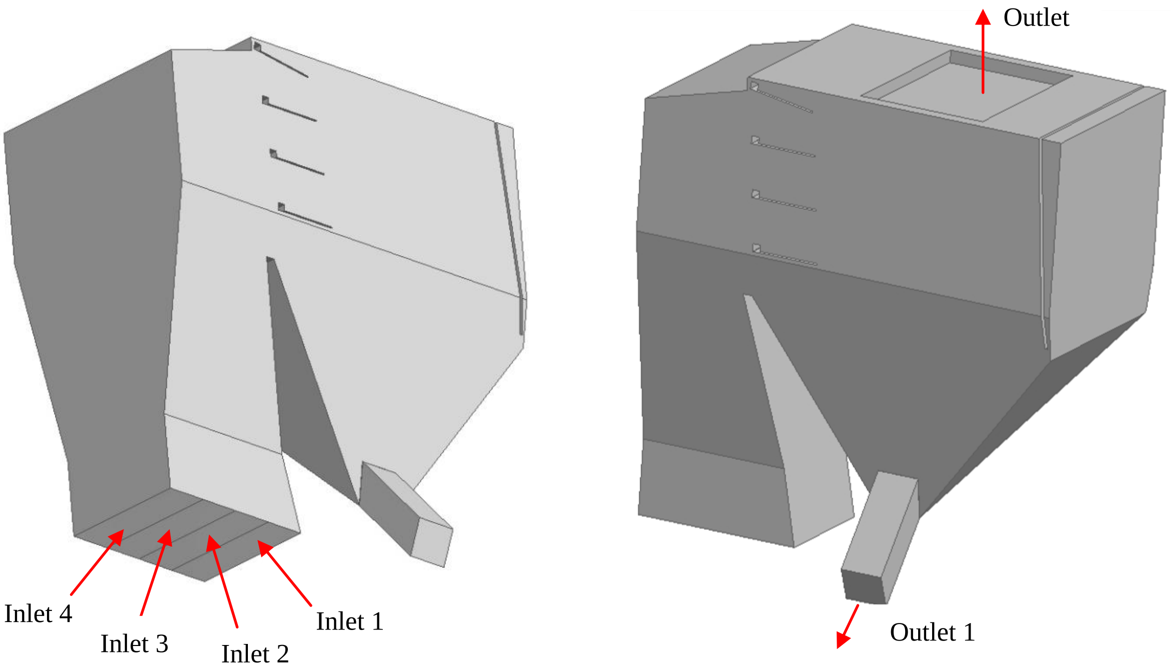


Figure 3. Inlet and outlet surfaces

3.1. Numerical grid

Two approaches are used in generating numerical grid. In first, thetraedron, as a finite volume base unit in entire volume, is used. As alternative option for generating the grid, hexaedrons are used. Comparisons of the quality of the grids are assessed through simulations regarding number of generated cells, calculated mesh quality parameters, accuracy of the obtained solutions and convergence time period. All checks showed that numerical grid generated by use of hexaedron as base finite volume unit is more suitable for use. Adjusting maximum number and values of largest and smallest generated cells, grid with 808 669 cells is considered as optimum solution. In both cases, it is notable that cell density around the flaps is considerably larger.

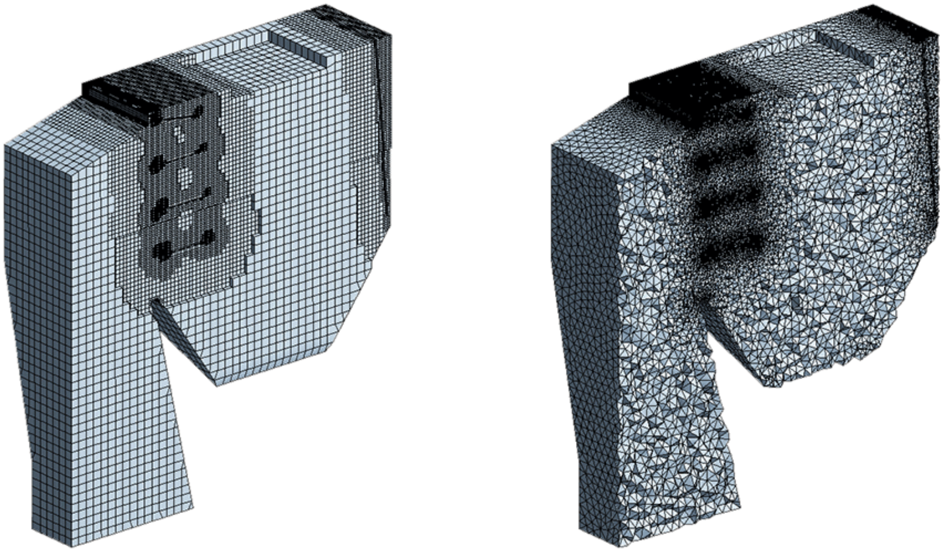


Figure 4. Middle - cross sections of analysed numerical grids

3.2. Boundary conditions

In very first step, simulations were performed only with gas phase, excluding the movement of solid particles. It is proposed that 85 % of total inflow leaves the separator, while 15 % is introduced in recirculation channel.

After obtaining considerable results, velocity magnitude of the gas phase is used for setting the velocity vector of the solid particles on the inlet surface.

Within the turbulent flow of air mixture, solid particles move stochastic and chaotic. The impacts against the separator walls are frequent. In case of impact, certain amount of kinetic energy of solid particle has to be reduced. It is proposed that amount of loosen kinetic energy depends mostly on angle of approach of particles against separator walls. After numerous simulations, it is considered that the values on the outlet are near to the measured values, if the lose of kinetic energy of solid particles is 30 % from the total in case of tangential approach and 70 % in case of perpendicular approach to the separator walls. Constant values are used for different positions of the lower flaps.

Different sets of particles distributions on the inlet are used until the residues on the sieves according to the obtained measurements are achieved.

Data from [5] are used for setting the boundary conditions. They are presented in the following table. Values represent results of measuring in channel on the outlet of the inertial separator.

Table 1. Results of measurements

Measured parameters		Markings	Units	Average values
Low heating value of the coal		H_d	кJ/кg	7703
Moisture content in coal dust		W^n	%	14,8
Sieve analysis	Residue on 1000 μm sieve	R_{1000}	%	6
	Residue on 200 μm sieve	R_{200}	%	30
	Residue on 90 μm sieve	R_{90}	%	65
Air mixture temperature		T	°C	170
Inlet mass flow of gas phase		$\dot{m}$	кg/s	109,27

4. Results of numerical simulations

4.1. Results of numerical simulations for the reference case

In reference case, lower flaps are positioned in horizontal plane, upper flap is rotated for 9° clockwise from horizontal and additional back-flap is almost parallel to the vertical separator wall. Upper flap position prevents high rates of the impacts on the collar outlet. Back-flap is positioned so that doesn't influence the velocity vectors of gas and solid phase in separators volume.

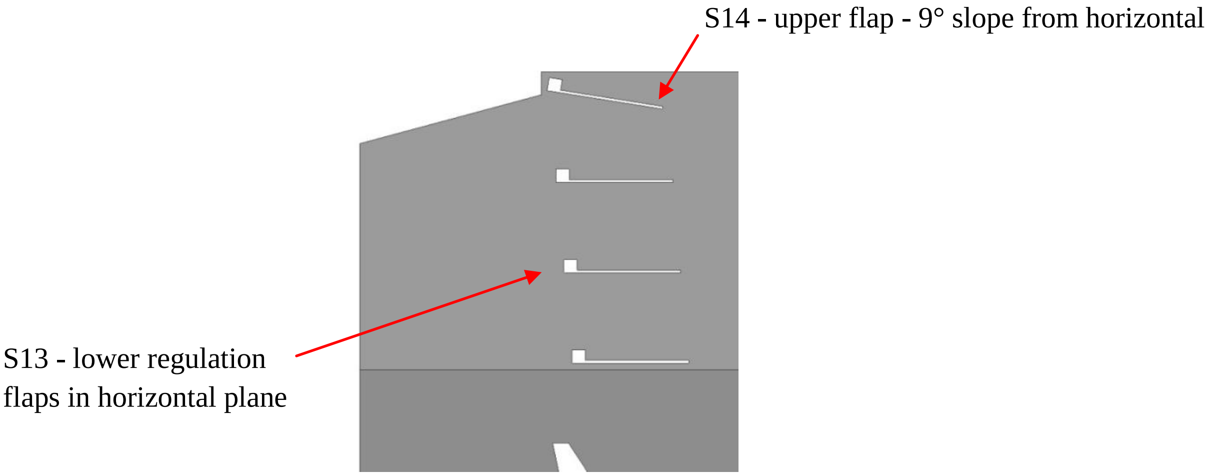


Figure 5. Reference position of S13 and S14 regulation flaps

In figure 6 velocity magnitudes of the gas phase in middle cross section are exposed. Velocity magnitudes varied in total range of 0 – 44,541 m/s. On the inlet surface velocity magnitude is around 22 m/s. High values are obtained in the vicinity of the flaps, as expected, according to the flow surface reduction. Significant increase occurs in the recirculation channel, where velocity magnitude reaches the values of approximately 44 m/s as consequence of reduced outflow surface.

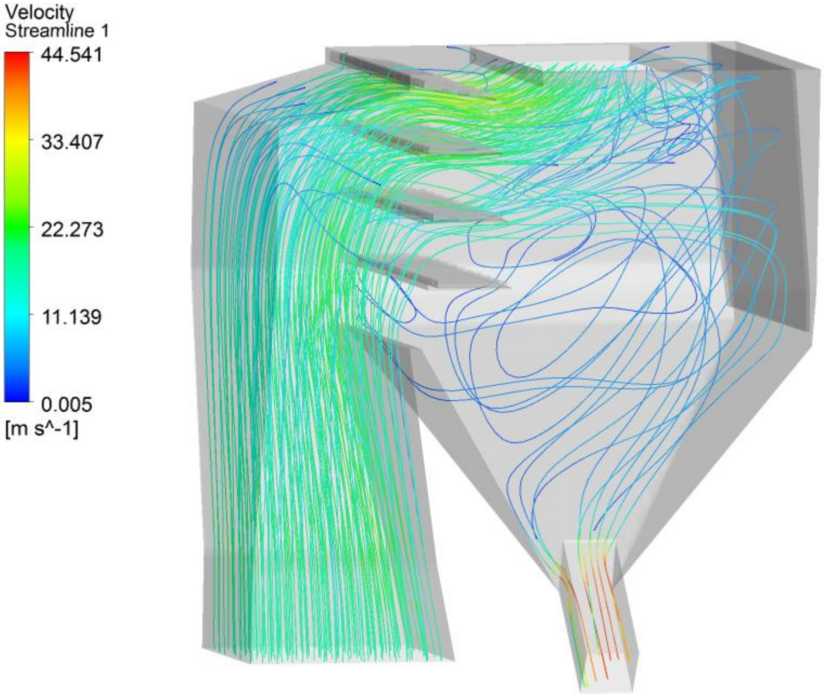


Figure 6. Streamlines of the gas phase

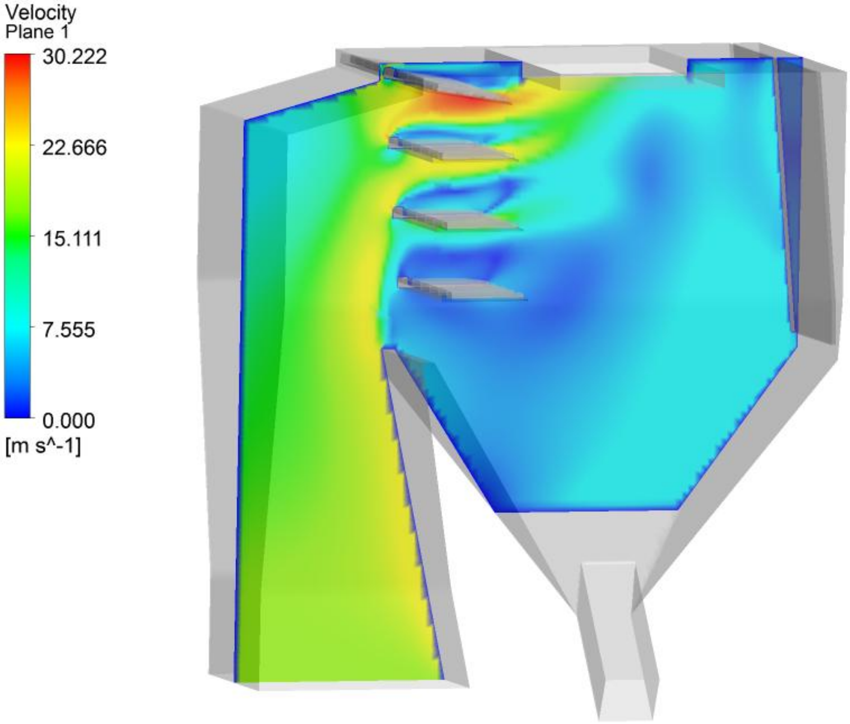


Figure 7. Velocity magnitude of the gas phase in middle - cross section plane

After solutions of simulations for “pure” fluid converged, solid particles has been introduced to the gas phase. Equality of the velocity magnitudes of gas phase and solid particles is applied. The diameters of used particles are 4000, 2000, 1500, 1000, 500, 200, 90, 50 μm. Particles with diameters from 4 to 1 mm are classified as “large”, while particles with diameters below 1 mm are classified as “small”.

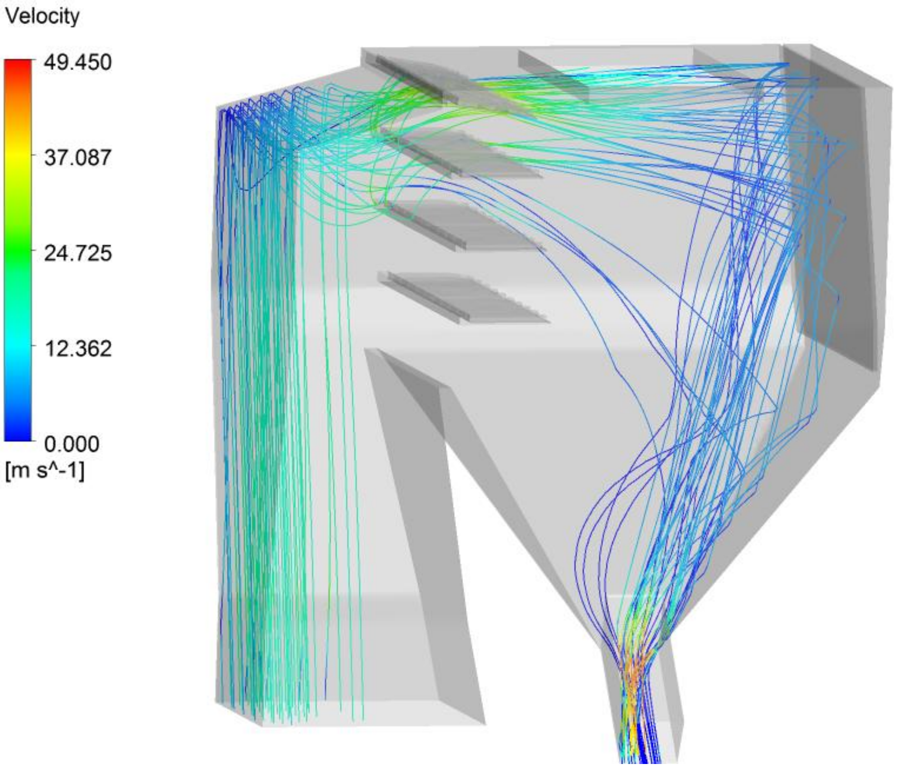


Figure 8. Trajectories of larger particles colored by the velocity magnitudes

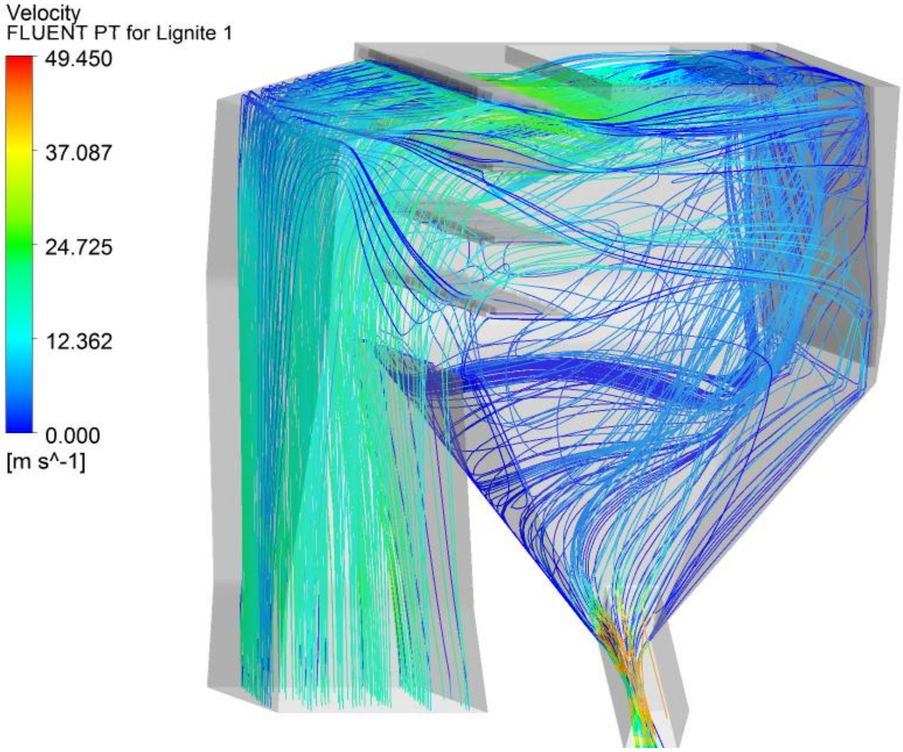


Figure 9. Trajectories of smaller particles colored by the velocity magnitudes

By comparing deviations of fluid flow streamlines and solid particles pathways, it is notable that larger, thus more massive, particles have lower resemblance rate with gas phase then smaller particles, as result of conspicuous influence of inertia force. Majority of larger particles pass near upper flap, which might be partialy used as a mechanism for regulating the outflow of the larger particles to the coal particles classifier. Significant reduction of the velocity magnitude of large and small particles, as for the gas phase, is obtained in separator volume above recirculation channel beneath lower flaps and additional back-flap.

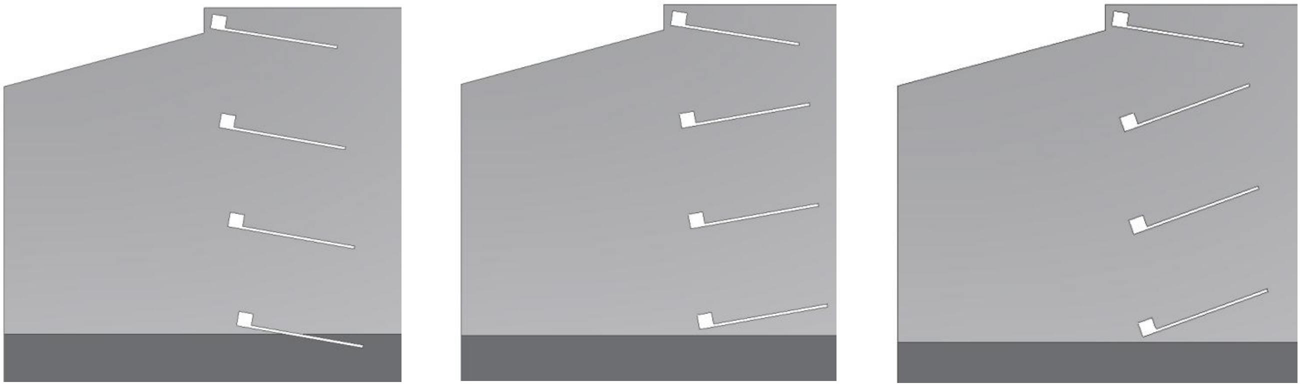
Results obtained in the simulations are in accordance with measured residues on the sieves on the real scale model, as shown in following table. That implies validity of proposed and used boundary conditions.

Table 2. Comparison of the results of numerical simulations and measured values on real scale model

Considered parameters		Markings	Units	Measurements	Results of numerical simulation – reference case
Sieve analysis	Residue on 1000 μm sieve	R_{1000}	%	6	6,352
	Residue on 200 μm sieve	R_{200}	%	30	30,1
	Residue on 90 μm sieve	R_{90}	%	65	65,41

4.2. Numerical simulations of considered positions of the lower flaps

As previously mentioned, the influence on finesses of grinding on the outflow surface is considered for the following positions of the lower flaps: -10°, +10°, and +20° according to mathematical positive rotation direction. Gas phase temperature, gas phase distribution, velocity vectors of the gas and solid phase, numerical grid and following boundary conditions are retained.

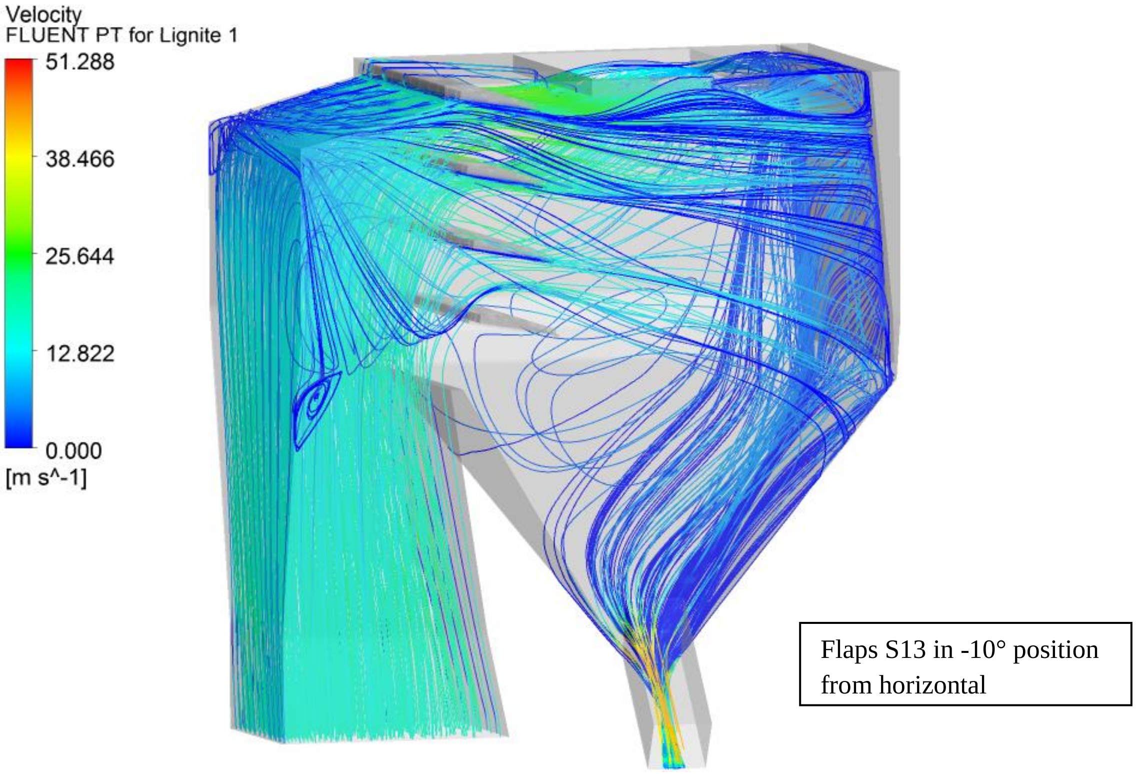

a) -10 °

b) +10 °

c) +20 °

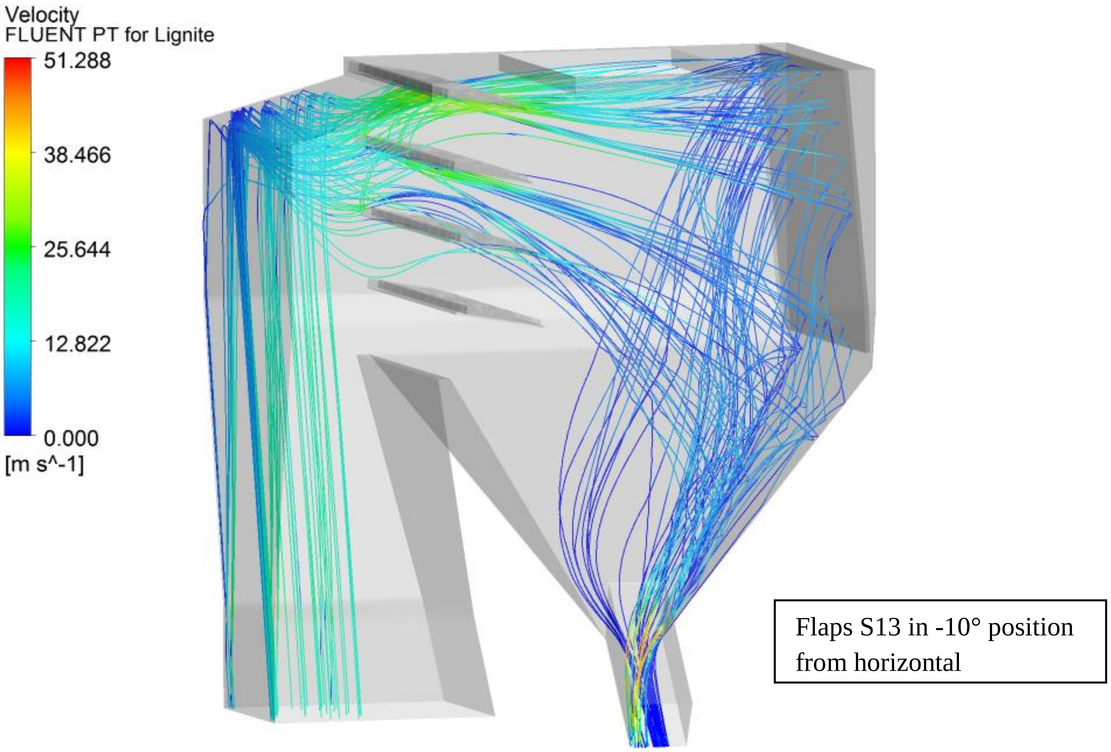
Figure 9. Considered positions of the S13 lower flaps

In the following figures pathways of the larger and smaller particles will be exposed.



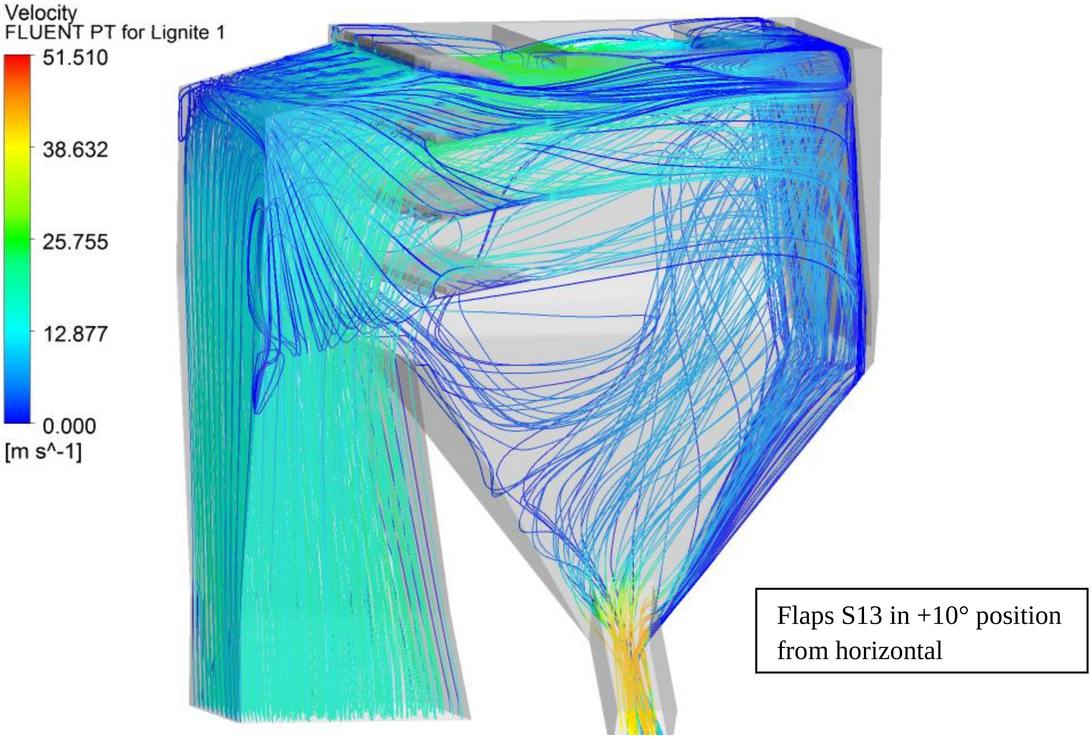
Flaps S13 in -10° position from horizontal

Figure 10. Trajectories of smaller particles colored by the velocity magnitudes



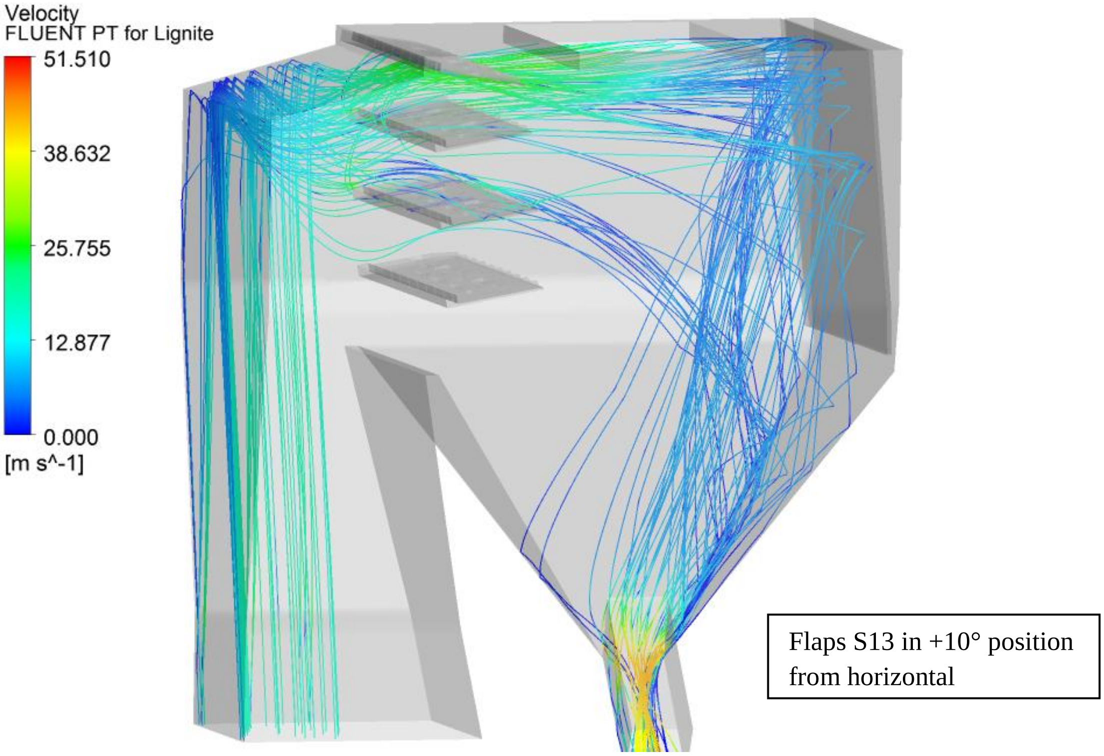
Flaps S13 in -10° position from horizontal

Figure 11. Trajectories of larger particles colored by the velocity magnitudes



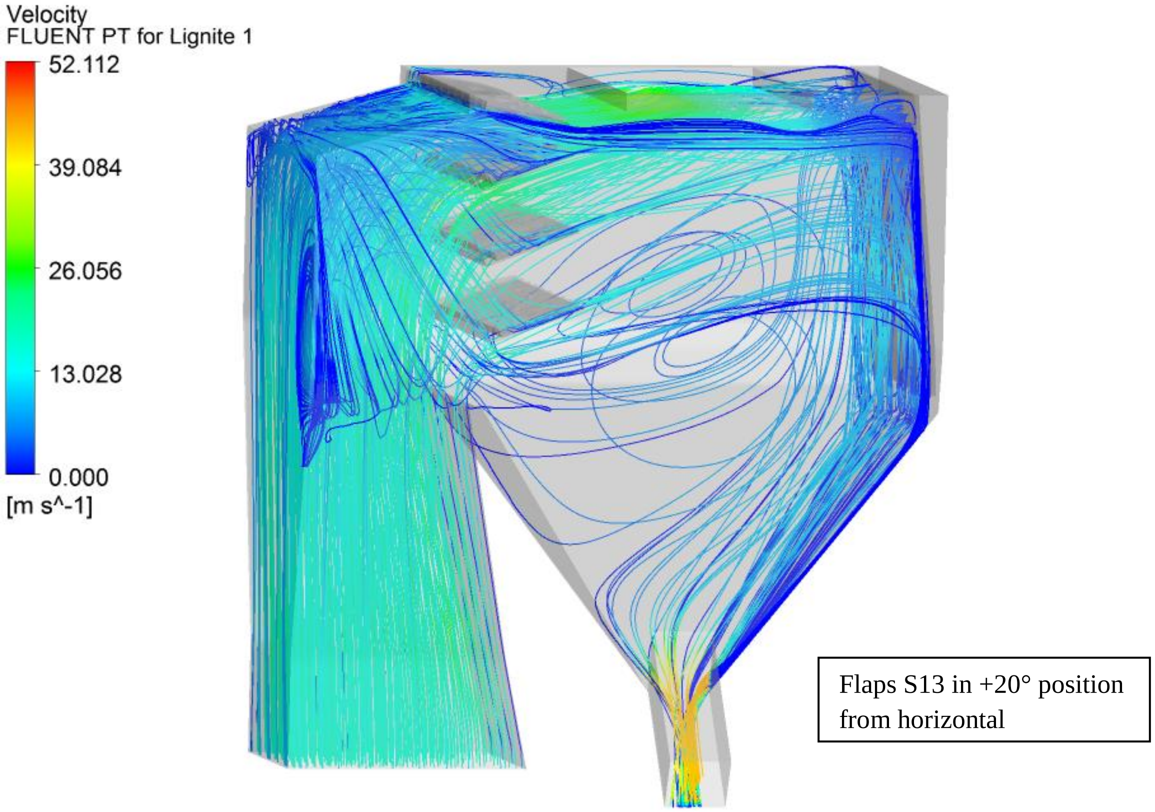
Flaps S13 in +10° position from horizontal

Figure 12. Trajectories of smaller particles colored by the velocity magnitudes



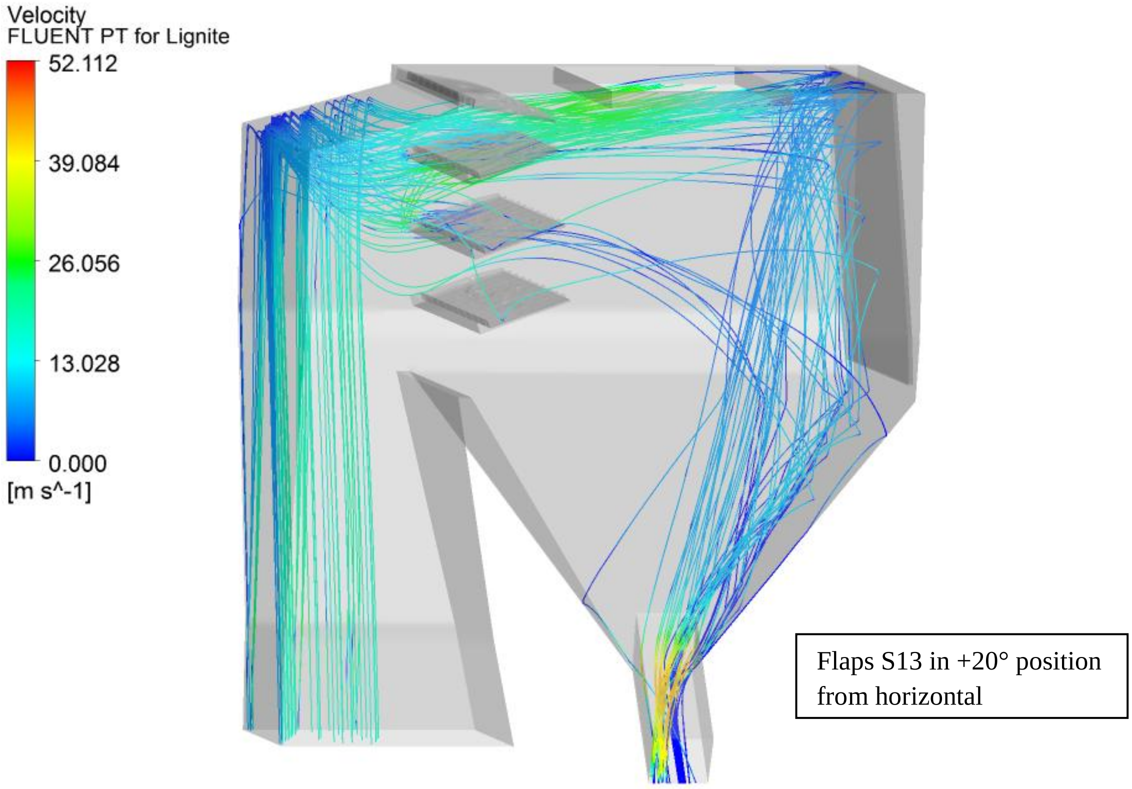
Flaps S13 in +10° position from horizontal

Figure 13. Trajectories of larger particles colored by the velocity magnitudes



Flaps S13 in +20° position from horizontal

Figure 14. Trajectories of smaller particles colored by the velocity magnitudes



Flaps S13 in +20° position from horizontal

Figure 15. Trajectories of larger particles colored by the velocity magnitudes

Table 3. Summary review of obtained results

Considered parameters		Markings	Units	Measured values	0° - reference case of lower regulation flaps	Lower regulation flaps considered positions		
						-10°	+10°	+20°
Sieve analysis	Residue on 1000 μm sieve	R_{1000}	%	6	6,35	5,77	6,41	10,77
	Residue on 200 μm sieve	R_{200}	%	30	30,10	32,68	32,5	35,06
	Residue on 90 μm sieve	R_{90}	%	65	65,41	63,12	64,8	64,11

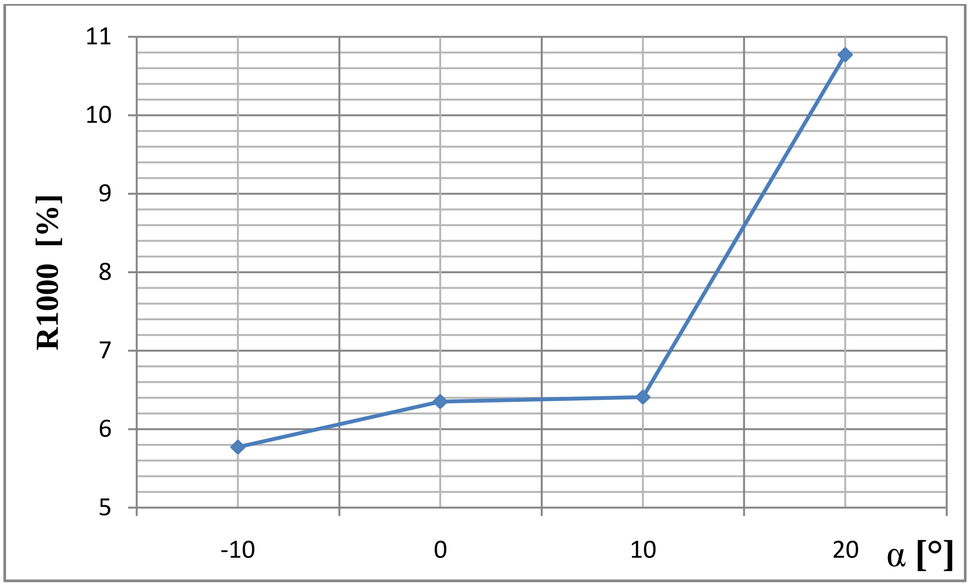


Figure 16. Inflection of R1000 (%) for different positions of the lower regulation flaps

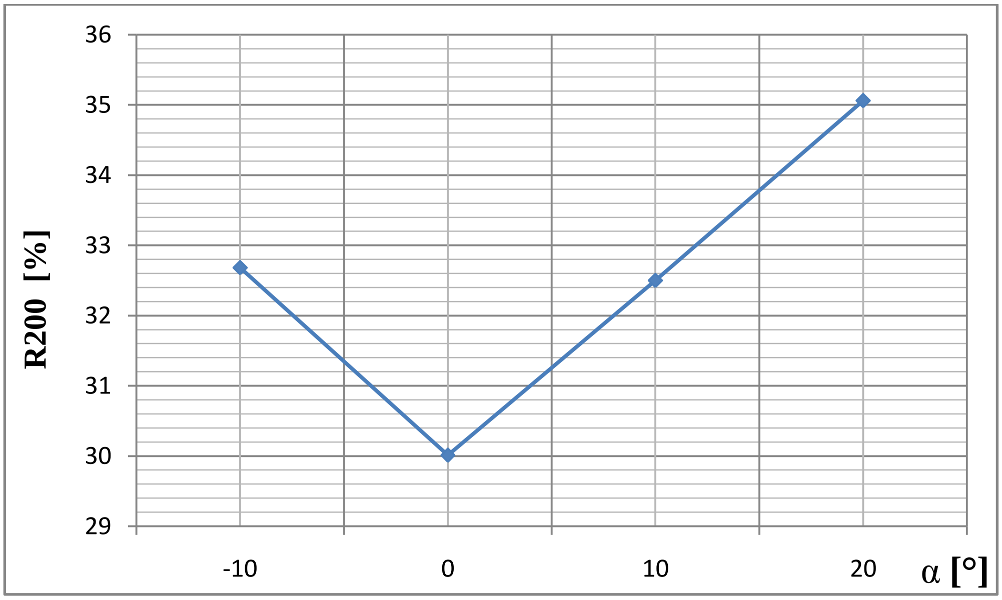


Figure 107. Inflection of R200 (%) for different positions of the lower regulation flaps

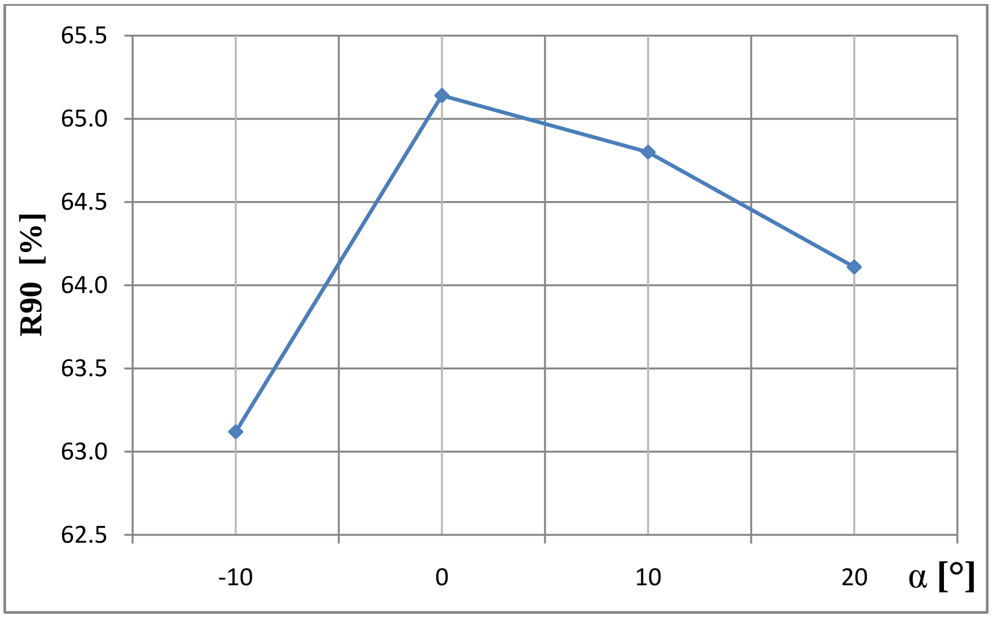


Figure 11. Inflection of R90 (%) for different positions of the lower regulation flaps

5. Results discussion

By comparing the streamlines of the gas phase and trajectories of the particles, according tho ther is diameter, it can be concluded that smaller particles (with diameters below 200 μm) form similar movement as fluid particles, regardless of the positions of the regulation flaps.

After entering the separator inlet channel, due to the velocity vector at the inlet surfaces and its mass, larger particles concentrate in left upper corner on the left of the regulation flaps. They throb/strike on walls of the separator, with significant reduce of theirs kinetic energy. In such conditions, by the influence of the gas phase, large particles continue to move in space between upper flap and top regulation flap, striving to the outflow surface. One part of the large particles hit the collar of the outlet channel and, by losing of kinetic energy, fall in the recirculation channel for re-milling. Other part of the total mass of the large particles, due to theirs mass and thus exerted inertia force, with insufficient influence of the gas phase, instead of turning into the outflow channel, they pass near outflow surface and strike the additional back – flap. Afterwards, from separation volume, they are brought to the separator hopper that introduce particles to the recirculation channel. Minority of the particles, with influence of the pressure forces on its surface and movement of surrounding gas phase, are introduced to the outflow channel.

In Figures 16 – 18, changes in residues on considered sieves is shown. Residues of particles with diameters larger then 1 mm, with rotating the flaps upwards, are in constant increase.

In distinction to them, content of particles in outflow medium with diameters between 200 μm and 1 mm reaches the minimum with flaps in reference position. With rotating regulation flaps upwards, proportion of these particles show intense grow.

Conversely to the trend shown on Figure 17., the content of smallest particles (diameters between 90 and 200 μm), used in simulation reaches the maximum in reference position of the regulation flaps with decrease of the theirs proportion for the flaps rotated upwards.

According to the Figures 16. to 18., it can be inferred that finesses of grinding decreases as regulation flaps rotate upwards. This can be explained with reduction in gas phase resistance in case of regulation flaps upper positions which implies more powerful influence of the gas phase on solid particles. Thus, trajectories of the larger particles are more similar to the streamlines of the gas phase. Then, the outflow mass of solid particles is considerably larger. Inverse change of all mentioned parameters is expected with rotating regulation flaps downwards from +20° slope from horizontal.

6. Conclusion

With use of contemporary computer tools and available technical documentation, simulations of two-component flow (gas phase – solid particles) in inertial separator of "TENT B2" thermal power plant have been performed. Inflection of the flow of solid particles on the outlet surface and in recirculation channel for different positions of lower regulation flaps is considered. Boundary conditions are adopted according to the measurements conducted on real scale facility.

Movement of the solid particles is solved with Lagrange approach which comprehend tracking of every single particle introduced to the flow volume. Variation of particles temperature, mutual collision of particles, change of particle mass and density and influence of the solid on the gas phase has been disabled. In interaction with flow domain only elastic collision is considered.

For determining gas phase streamlines, Oiler approach of control fixed volumes is applied. Performed numerical simulations are based on solving the two-equations k-ε turbulent model implemented in used software. Considered flow is incompressible, steady and three-dimensional with constant temperature in entire flow domain. Chemical interaction with solid particles is excluded.

Due to the simplicity in use and implemented numerical calculation algorithms, commercial software pack FLUENT is used. Used input values are in accordance with proposed assumptions and measurements made on real scale model.

Numerical results clearly demonstrate modification of the residues of solid particles on sieves of 1000, 200 and 90 μm in dependence of the positions of the lower regulation flaps. Rotation of the regulation flaps upwards lessens the finesses of grinding of passed solid particles, with evidenced increases of the amount of particles introduced to the mill classifier. Downward rotation of the flaps has inverse influence on observed parameters.

In further analysis, in order of having more detailed view in change of important flow parameters, it is recommended to examine field of pressure, with equal boundary conditions based on performed measurements, that occurs in entire flow domain.

7. References

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