ASSESSING THE IMPACT OF SPECIFIC WEIGHT OF DIFFERENT-SIZED PARTICLES ON OPERATIONAL PERFORMANCE OF COAL PREPARATION PLANT

by

Ognjen S. STAMENKOVIĆ *, ***Goran M. STUPAR, and Dragan R. TUCAKOVIĆ***

Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia

Original scientific paper
https://doi.org/10.2298/TSCI2301103S

In case of firing pulverized coal in power steam boiler certain fuel preparation process has to be taken in order to ensure stable and optimal combustion in boiler furnace. Before entering furnace low caloric coal is introduced from coal bunker to the coal preparation system where milling/pulverization and drying processes of raw large coal particles are conducted. For the purpose of defining fineness of grinding of pulverized coal mill gaseous mixture at mill outlet is introduced to the separator where large coal particles, separated from outgoing mill gaseous mixture, are recirculated to mill for regrinding. In this paper character of two-phase flow in inertial separator at milling plant in TPP Nikola Tesla Unit B under various operating conditions has been analyzed. The CFD approach has been used for calculating two-phase flow in separators flow domain. Measurement data taken on site along with results of performed heat balance calculations of milling plant have been used for validating calculation model as well as for setting appropriate boundary conditions in CFD model. The CFD calculations has been performed for different positions of all regulating flaps, recirculation rates of gaseous phase and values of specific weight of solid phase in two-phase mixture. For evaluating separators operating performance at different operating regimes changes of milling capacity and fineness of grinding of pulverized coal at separators outlet have been observed. Additionally, deviation rate of trajectories of different-sized particles to the streamlines of gaseous phase has been examined.

Key words: *inertial separator, fan mill, coal particles, mill gaseous mixture, numerical modelling*

Introduction

Although recent COVID-19 pandemic caused permanent drops in electricity demands and production electricity market recovered in second part of 2020 causing drop of only 1% on year level and continued to grow in 2021 [1]. Reducing electricity production throughout the world was mostly provided by decreasing activities of thermal power sectors. In recovery period consumption of fossil fuels for producing electricity has been increasing with intensity similar to the period before 2020. Ongoing crisis caused by political and military instabilities in Ukraine provoke new disturbances on electricity markets pushing fuel prices up [2] and forcing states energy sectors to reconsider existing plans and to relay its per-

* Corresponding author, e-mail: ostamenkovic@mas.bg.ac.rs

spectives on domestic reliable energy sources. Along with that, similar to the trends before 2020, developing countries continue to slowly increase coal consumption while developed countries reduce it, rather, cautiously [3].

Electricity production in Serbia is mostly based on developed thermal power sector which participates in total production for almost 70% [4]. According to available data Serbia holds 14th place [5] regarding its raw coal reserves which might last (at present consumption rates) for at least next half-century.

Increasing prices of electricity forces engineering sector to further optimize existing thermal power capacities. This includes implementing technologies for reduction of pollutants emissions, increasing reliability of plants and its energy efficiency during operation.

Coal pulverization and combustion have been challenging since their discovery and are considered as never-ending research subjects for academic community. Both processes include mass and energy exchange at high temperatures differences between phases and boundaries of flow domain as well as particles dissolution in milling plants. Many independent and correlated factors have impact on their dynamics and overall processes outputs.

Thus, in order to ensure stable operation of boiler plant and combustion process, before entering the boiler furnace raw coal is introduced to the milling plant. In fig. 1 individual coal preparation system scheme with fan mill and closed coal drying loop is shown. Raw coal particles are brought to the fan mill – 3, from coal hopper – 1 *via* coal feeder – 2 where drying and milling processes are performed. For the purpose of adjusting finesses of grinding of coal particles entering the boiler burners mill gaseous mixture after fan mill (consisted of pulverized coal and carrier fluid) is introduced to the separator – 4 where larger particles are separated from rest of mixture and recirculated to the mill *via* duct – 5 for additional grinding. Mill gaseous mixture leaving the separator is brought to the mill classifier – 6 where the bulk of mixture is spilt and distributed to the stages of multistage burner – 7. For the purpose of drying and carrying solid phase throughout milling plant hot gases are recirculated from furnace outlet – 8. Temperature of mill gaseous mixture is regulated by introducing hot air from air pre-heater into milling plant – 9. Cold air intake – 10, is mainly used during fan mill start-up as well as for urgent cooling of mill gaseous mixture during mill operation.

There are many types of separators operating in various milling plants. All of them are mostly named according to the predominant particle force by which separation process of larger particles is obtained (centrifugal, inertial, gravitational, *etc*. [6, 7]). In TPP Nikola Tesla Unit B inertial mill separator is applied where separation process is achieved by application of particles inertia force. Operational performances of such separators are mostly influenced by the separation volume geometry, position of maneuverable regulating flaps as well as flow characteristics of two-phase mill gaseous mixture. Changes in these parameters might cause significant variations in overall milling capacity, finesses of grinding and recirculation rate of coal in mill.

Fineness of grinding at mill outlet influences operation of mill classifier responsible for distribution of gas and solid phase of mill gaseous mixture through stages of multistage burners. Inappropriate distribution through burner stages may cause moving high temperature flame core toward furnace outlet which will increase flue gas outlet temperature and decrease heat transferred toward heat receiver in water wall pipes. Also, unfavorable fineness of grinding might lead to increase of share of unburned fuel at furnace hopper which directly reduces boiler efficiency rate and, consequently, overall efficiency rate of power plant. Inadequate position of regulating flaps might reduce mill ventilation and milling capacity and, consequently, limit overall boiler output at some point.

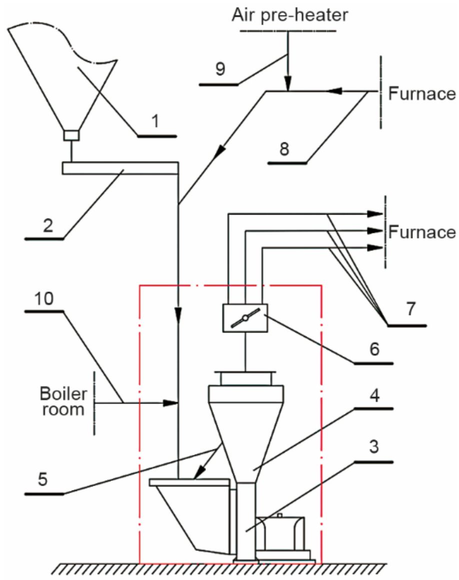

Figure 1. Individual system for coal preparation with closed coal drying loop; *1 – coal hopper, 2 – coal feeder, 3 – fan mill, 4 – inertial separator, 5 – separation recirculation duct, 6 – mill gaseous mixture classifier, 7 – multistage burner, 8 – recirculation of hot gases, 9 – primary air intake, 10 – cold air intake for urgent mill cooling*

Thus, it is necessary to closely investigate performance of separator in different operation regimes in order to provide data by which it would be possible to predict separator output and to optimize its operation.

In this paper results of numerical calculation of two-phase flow in mill inertial separator at TPP Nikola Tesla Unit B are presented. Measurement data collected on site along with results of heat balance calculations of milling plant have been used to provide appropriate model boundary conditions in calculation procedures. Calculation has been performed for different position of all regulating flaps, different gas phase recirculation rate and various values of specific weight of coal particles.

Pneumatic transport of solid phase is commonly applied in many industrial applications. Such fluid flow arrangement has been studied for decades and, due to its complexity, there are no exact mathematically derived solutions able to be easily applied in real scale plants. Along with that, there are many studies, books and papers in which specific problems of two-phase flow are consider. Mathematical background of such flow is well described in [8, 9], while summarized results of various researches are presented in [10].

However, there are not many publications in which separation process in inertial mill separator is examined. Reason to this might be found in modest scope of available measurements performed on milling plants in thermal power units. Also, during measuring operational parameters control volume is set as shown in fig. 1 by dotted line, which implies that there is no available data on two-phase flow parameters at separators inlet. Such occurrence requires additional analysis in order to iteratively detect appropriate mass flow and particles distribution of solid phase in inlet cross-section.

In comprehensive overview of modern lignite drying technologies applied in power plants presented in [11] authors state that there are three milling plant types used for efficient drying and milling of coal. All three configurations are shown in fig. 2 in [11]. First type of mill separator can be considered as similar to the one analyzed in this paper. Such type of separator might work in configurations with movable or static flaps. In paper it is stated that separators supplied with static flaps might achieve residue on 1000 μm sieve between 3% and

5% while reside on sieve of 90 μm goes usually from 70% to 90%. Other two configurations (vapour separator classifiers and multistage beater mill) correspond to the different coal drying and pulverization schemes and, thus, will be not commented here. Although paper does not provide any calculation results it consists important data on expected mill separator performances based on operation of existing plants.

In [12] simulation of two-phase gas flow in milling plant has been presented. Full geometry of mill impeller, inertial separator and entire mill gaseous mixture duct along with pulverized coal burner have been used in CFD calculations. In CFD calculations two-phase flow has been treated by Oiler-Oiler approach. Drying and breakage process of solid phase has been neglected. The aim of study was to examine centrifugal classifier performances located between separator and multistage burner in two different operating regimes. In calculations geometry of inertial separator as well as positions of regulating flaps has been kept while separation process in mill separator has not been commented in particular.

Distribution of mill gaseous mixture between stages of multistage burner in dependence of position of flap-type classifier within vertical mill gaseous mixture duct has been analyzed in [13]. Inlet boundary conditions has been set according to the measurements taken on site in vertical gas duct. Distribution of solid phase in inlet cross-section has been set as uniform while particle size distribution has been applied by use of Rosin-Ramler-Spearling (RRS) law. Change of mill gaseous mixture distribution through burner stages in case of rotating flap-type classifier is given in [13]. Separation process occurred in separator has not been analyzed.

In [14] calculation algorithm for two-phase flow in mill inertial separator has been presented. Character of mill gaseous mixture flow within separator domain located at coal preparation system at TPP Tuzla Unit III has been analyzed. Operational performances of inertial separator has been assessed by performing CFD calculations for different positions of regulating flaps. Distribution of solid phase at separator outlet as well as milling capacity and fineness of grinding have been commented in particular. In dissertation influence of solid phase specific weight and gas flow recirculation rate on main inertial separator performances have not been analyzed.

In [15] results of optimization of milling plant of steam boiler P-64 of 300 MW unit of TPP Ugljevik. This study comprised numerous actions taken in order to provide efficient combustion in furnace with aim to lower flue gas temperature at semi-radiant superheater outlet. Among others, cold pre-purge of air tract, adjusting centrifugal classifiers at burners inlet as well as control of excessive air in furnace has been provided. Operational parameters of mill and separator have not been adjusted nor commented in paper.

Dependence of distribution of solid phase in outlet cross-section from position of regulating flaps in inertial separator is given in [16]. It is shown that solid phase is mostly concentrated near back wall of mill gaseous mixture duct when flaps are positioned toward separators hopper. Solid particles move toward front wall of duct when flaps are rotating toward separator outlet cross-section. However, larger portion of solid phase remains in one half of the outlet cross-section bounded by back wall of mill gaseous mixture duct.

Inertial separator geometry

Geometry of separator used in CFD calculations is identical to the real facility set at TPP Nikola Tesla Unit B and is shown in figs. 2(a)-2(d). Mill gaseous mixture after milling and drying in fan mill enters inertial separator through inlet cross-section – 1. After vertical separator duct – 2 two-phase mixture turns for 90°, and passes through short horizontal section – 3, in which two sets of regulating flaps are positioned. First flap set, S13, is consisted of three flaps linked to a common drive remaining parallel to each other when rotating. Regulating flap, S14, is placed right below separators ceiling and may be independently rotated from flaps, S13. The S12, large plane-type flap, is positioned near back wall of separators volume and is of independent drive too. Permanent positions of all flaps define velocity profile of gaseous phase of mill gaseous mixture which in interaction with solid phase influences particles inertia forces. Intensity and direction of every particle inertia force depends of particle shape, dimension and specific weight and is of decisive importance weather particle will continue to move along with mill gaseous mixture and leave separator through outlet cross-section – 4 or fall into separator hopper – 5 and continue to move through recirculation duct – 6 toward fan mill housing. For the purpose of setting appropriate distribution of coal particles at separators inlet cross-section – 1 is divided on four (I-IV) equal surfaces, as shown in fig. 2(b).

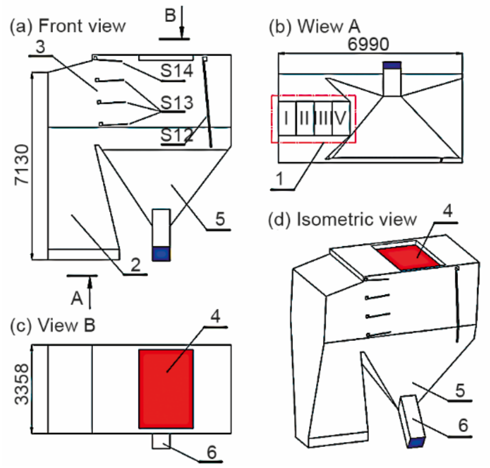

Figure 2. Geometry model of inertial separator used in CFD calculations; *1 – inlet cross-sections, 2 – vertical separator duct, 3 – horizontal section, 4 – outlet cross-section, 5 – separators hopper, and 6 – recirculation duct*

Measurement data, results of heat balance calculations

During retrofit of mills in 2009-2010 in TPP Nikola Tesla Unit B measurements on milling plants have been performed in various operating regimes. Milling plant performance has been assessed before and after reconstruction of mill impeller and housing while geometry of inertial separator remained. All data has been summarized and presented in report [17]. Measurements have been performed by Innovation Center of Faculty of Mechanical Engineering in Belgrade under following circumstances:

– Power plant unit operates with power output ≈ 600 MW.
– During measurements equalized sortiment of coal is to be provided, as much as possible.
– Flow of primary air is set at 25000 Nm^3/h.
– Under constant flow of primary air mill is to be operated with coal as much as needed to maintain mill gaseous mixture temperature ≈ 165 °C.
– Rounds per minute of mill impeller is to be maintained at 450° per minute.
– Sliding flap on coal feeder is to be kept open.
– Coal layer height on coal belt conveyor is to be kept at 300 mm, in case of a need is to be raised to 330 mm.
– Specimens are to be collected for every measuring regime on coal feeder for the purpose of determining Proximate analysis and grindability ratio.
– For every measuring regime after collecting specimen and conducting proximate analysis sieving on 60 mm and 30 mm sieves is to be performed.

Data recorded on mill No. 12 on 04.05.2009 has been taken as most representative case. Measurement data in this regime are presented in first column in tab. 1. In order to check measured values and to expand measurement data with additional operational parameters heat balance calculation of milling plant has been performed. Reduced overview of data from heat balance calculation are presented in 6th column of tab. 1. Calculations are conducted completely according to procedure given in [6, 7]. Certain parameters in tab. 1 have been averaged (mill gaseous mixture temperature, velocity, *etc*.) according to the mass flow of mill gaseous mixture or solid phase throughout the burner stages.

Table 1. Measuring data taken on mill no. 12, results of heat balance calculation of milling plant

No.	Parameter	Notation	Unit	Mill No. 12	
				Measuring results	Calculat. results
1.	Date	/	/	04.05.09.	/
2.	Time in operation	/	[h]	810	/
3.	Primary air		[Nm^{3}h^{-1}]	25000.0	25109.0
4.	Positions of flap S14/S13	/	[º]	9/42	9/42
5.	Milling capacity (averaged)	B	[th^{-1}]	135.23	134.96
			[kgs^{-1}]	37.56	37.49
	– by use of coal feeder geometry	B_{CF}	[th^{-1}]	133.1	/
	– on pulverized coal side	B_{PC}	[th^{-1}]	136.3	/
	– on belt conveyor	B_{BC}	[th^{-1}]	130.8	/
6.	Vaporized moisture in milling plant	ΔW	[%]	41.50	39.0
7.	Mass flow of solid phase at separators outlet	B_{SO}	[kgs^{-1}]	23.726	23.75
8.	Specific weight of mill gaseous mixture	ρ_{MGM}	[kgN^{-1}m^{-1}]	/	1.166
			[kgm^{-3}]	/	0.749
9.	Mill ventilation (volume flow of mill gaseous mixture at separators outlet)	$\dot{V}_{m}$	[Nm^{3}h^{-1}]	290282.0	291507.0
9.1.	Flow of recirculation gases at furnace outlet	$\dot{V}_{rc}$	[Nm^{3}h^{-1}]	/	123361.6
9.2.	Flow of cold air	$\dot{V}_{sv}$	[Nm^{3}h^{-1}]	/	78389.2
9.3.	Flow of vaporized moisture in mill	$\dot{V}_{H_2O}$	[Nm^{3}h^{-1}]	/	64647.2
10.	Mill gaseous mixture temperature (averaged)	t_{asm}	[K]	424.9	425.0
			[ºC]	151.8	152.0
	– Lower stage of multistage burner	$t_{asm,\mathrm{ls}}$		141.0	/
	– Middle stage of multistage burner	$t_{asm,\mathrm{ms}}$		148.0	/
	– Upper stage of multistage burner	$t_{asm,\mathrm{us}}$		172.0	/
11.	Mill gaseous mixture velocity	w_{asm}	[ms^{-1}]	20.88	20.14
	– Lower stage of multistage burner	$w_{asm,\mathrm{ls}}$	[ms^{-1}]	20.0	/
	– Middle stage of multistage burner	$w_{asm,\mathrm{ms}}$	[ms^{-1}]	19.0	/

Table 1. Continuation

No.	Parameter	Notation	Unit	Mill No. 12	
				Measuring results	Measuring results
	– Upper stage of multistage burner	$w_{asm,\mathrm{us}}$	[ms^{-1}]	23.3	/
12.	Moisture in pulverized coal	W_{P}	[%]	16.47	16.80
	– Lower stage of multistage burner	$W_{\mathrm{P,ls}}$	[%]	18.3	/
	– Middle stage of multistage burner	$W_{\mathrm{P,ms}}$	[%]	16.4	/
	– Upper stage of multistage burner	$W_{\mathrm{P,us}}$	[%]	14.0	/
13.	Reside on 1000 μm sieve	R_{1000}	[%]	9.47	9.50
14.	Reside on 200 μm sieve	R_{200}	[%]	44.77	44.0
15.	Reside on 90 μm sieve	R_{90}	[%]	70.758	70.7
16.	Oxygen concentration in carrier fluid at milling plant inlet	$\mathrm{O}_{2,\mathrm{inlet}}$	[%]	6.4	6.74
17.	Oxygen concentration in mill gaseous mixture at separators outlet	$\mathrm{O}_{2,\mathrm{outlet}}$	[%]	11.93	12.22
18.	Carrier fluid temperature	t_{CF}	[ºC]	915.0	912.4
Ultimate analysis – raw coal					
19.	Lower heating value* (LHV)	H_d	[kJkg^{-1}]	7330.0	
	Moisture content	W^r	[%]	51.1	
	Ash content	A^r	[%]	13.9	
	Carbon content	C^r	[%]	22.2	
	Hydrogen content	H^r	[%]	2.2	
	Oxygen content	O^r	[%]	10.0	
	Nitrogen content	N^r	[%]	0.5	
	Combustible sulfur content	S_a^r	[%]	0.1	

* The LHV value has been determined in laboratory conditions and might deviate to the value calculated *via* equation given in [7] by use of ultimate analysis results data.

Mathematical modeling of two-phase flow in inertial mill separator

Modeling solid phase movement

Two-phase flow has been modeled using Oiler-Lagrange approach which implies solving gas phase flow equations using Oiler frame of control volumes while movement of solid phase is determined by solving momentum equations based on well known Newton's laws. All calculations have been carried out in ANSYS FLUENT software package. Lagrange approach has been applied through discrete phase model (DPM) explained in [18] extensively used in many industrial CFD calculations [10].

Solid particles have been considered as inert spheres of different diameter with constant mass and specific weight. In praxis, it is to be expected that mass of coal particles in separator is generally not constant. Pulverized coal continues to lose mass due to the occurrence of ending phase of drying process in separators domain. It is to be stated that drying process in separator is of much lower intensity in comparison with process in mill impeller. Pulverized coal in separator loose small part of its mass causing increase in mass--flow of gas phase, and, consequently, higher velocities of gas phase throughout the domain. Opposite to that, drying process is followed by lowering gas phase temperature, provoking decrease in velocity magnitude in case of compressible fluid. These two effects collide and, even, at some extent repeal one another which makes simplification of mathematical model by neglecting mass transport between phases justified.

Collision between solid phase and domain boundaries has been modeled by use of hard sphere model. In this model bodies in contact are considered as rigid while their velocity components (in tangent and normal direction regarding contact geometry) before and after impact are linked *via* restitution coefficients, as described in [9] and applied in [19]. Values of restitution coefficients used in CFD simulations corresponds to the values adopted in [20].

Full Max-Railey equation given in [8, 9] summarizes all forces that might be applied on rigid sphere that moves through surrounding fluid. Simplification of this equation has been performed by neglecting forces related to the non-stationary two phase flow (Basset force, virtual mass force). Influence of Saffman force is also neglected due to the fact that solid phase moves in area with high gas phase velocity magnitude, far from domain boundary and areas with strong velocity gradients in direction normal to the particle velocity vector. Thus, final form of solid particles movement equation can be written as:

$$\underbrace{m_\mathrm{p}\frac{\mathrm{d}}{\mathrm{d}t}(\vec{\mathrm{U}}_\mathrm{p})}_{\text{I. f.}} = \overbrace{R_\mathrm{p}(\vec{\mathrm{U}}-\vec{\mathrm{U}}_\mathrm{p})}^{\text{D. f.}} + \underbrace{m_\mathrm{p}g}_{\text{G. f.}} - \overbrace{V_\mathrm{p}\nabla P}^{\text{P. f.}}) \tag{1}$$

where I. f. [N] is the inertia force, D. f. [N] – drag force, G. f. [N] – gravitational force, P. f. [N] – the pressure-gradient force, m_p [kg] – the particle mass, $\vec{\mathrm{U}}_\mathrm{p}$ – [ms^{-1}] – the particle velocity vector, $\vec{\mathrm{U}}$ [ms^{-1}] – the gas phase velocity vector, g [ms^{-2}] – the gravitational constant, V_p [m^3] – the particle volume, ∇P [Pam^{-1}] – the pressure gradient, and R_p [–] – the particle drag function calculated by use of following equation:

$$R_\mathrm{p} = 0.5\rho A_\mathrm{p} C_\mathrm{D}\left|\vec{\mathrm{U}}-\vec{\mathrm{U}}_\mathrm{p}\right| \tag{2}$$

where ρ [kgm^{-3}] is the particle specific weight, A_p = [m^2] – the particle cross-section, and C_D [ms^{-1}] – the drag coefficient of spherical particles calculated by the following equation:

$$C_\mathrm{D} = \frac{24}{\mathrm{Re}}(1+0.15\,\mathrm{Re}^{0.687}) + \frac{0.42}{1+4.25\cdot 10^4\,\mathrm{Re}^{-1.16}} \tag{3}$$

where Re [–] is the Reynolds number of spherical particle.

As previously said, measurements on milling plant are taken on its boundaries showed in fig. 1 by red line. Thus, distribution and mass-flow of solid phase in separator inlet remains unknown. In order to establish appropriate solid phase boundary conditions at separators inlet numerous calculations have been performed with aim to detect groups of particles and their distribution which would provide calculation results at separators outlet close to the measured values given in tab. 1. As sieving of pulverized coal specimen taken during measurement was performed on sieves set of 4.0, 2.0, 1.0, 0.5, 0.2, and 0.09 mm sieves, groups of particles was chosen such that there are two different diameters of particles between each of two adjacent sieves. It is proposed that distribution of groups is such that smaller particles enters separators domain through Sections III and IV while larger particles are concentrated mostly in Sections I and II, fig. 2. Non-uniform distribution of groups occurs due to centrifugal force acting on particles in mill impeller. Final distribution used in all performed calculations is given in fig. 3.

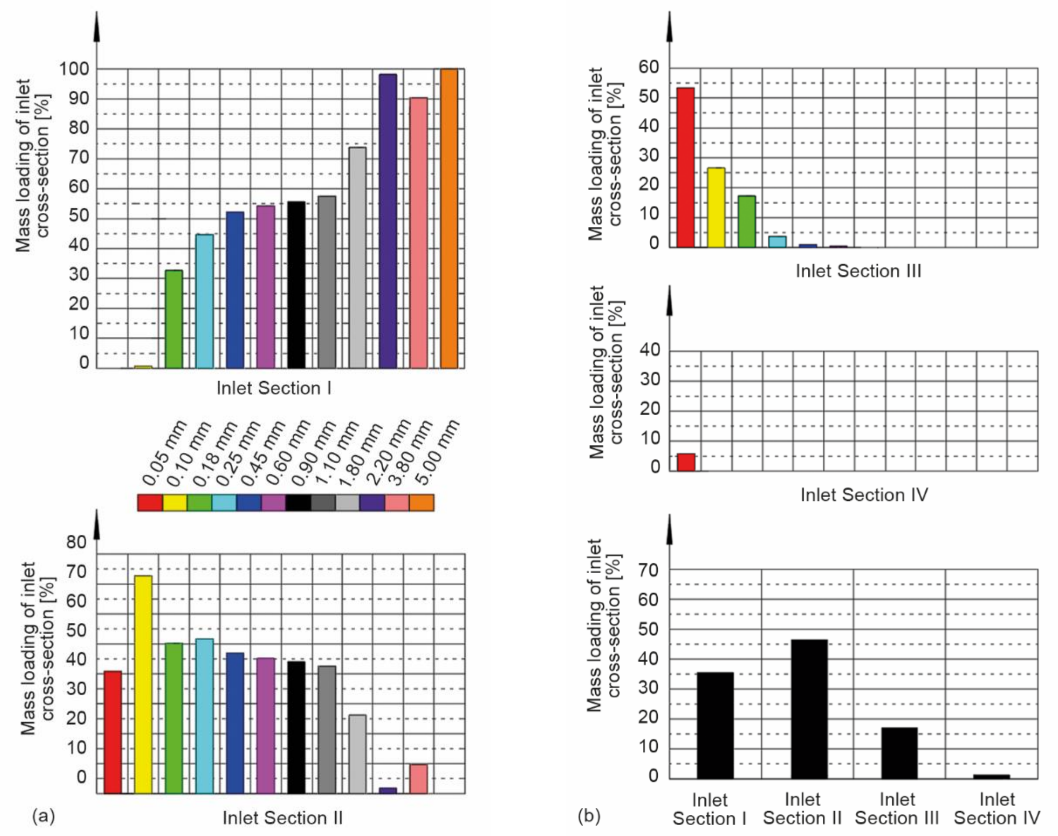

Figure 3. Distribution of particle groups in inlet sections of inertial separator

In fig. 3 might be also noted that largest portion of particles mass-flow enters through Section II. Lowest particle mass loading is detected in Section IV consisted of smallest particle group.

Modeling gas phase flow

In Oiler approach gas phase has been treated as continuum. Streamlines of gas phase are determined by solving Reynolds-averaged Navier-Stokes equations. Flow is considered as viscous, turbulent, incompressible, steady, 3-D, adiabatic and chemically inert. Turbulence has been modeled by use of k-ε two equation turbulence model. As previously said, influence of solid phase on gas phase flow is neglected. Such simplification reduces overall two-phase fluid-flow model on solving two transport equations of gas phase (mass and momentum) given and explained in [14]. There is no need for solving energy equation since there is no heat flux between phases or on boundaries of considered domain.

Mass-flow boundary conditions are applied at separators inlet and outlet cross-section. Distribution of fluid throughout inlet sections is uniform and inlet velocity is calculated by use of mill gaseous mixture specific weight obtained in milling plant heat balance calculation. Distribution of gas phase at outlet cross-sections is, for the need of validating calculation model, set so 85% of fluid leaves the separator domain through outlet cross-section while 15% is returned to the mill *via* recirculation duct.

In fig. 4. velocity field in characteristic cross-sections is shown. It can be seen that larger portion of gas phase passes through area between flap S14 and upper S13 flap while other mid-passes in flap region remain with significantly lower fluid mass-flow. This occurrence might be explained by synergy of few construction details. For instance, inlet vertical duct converges as it approaches to the region where flaps are positioned. As it shown in fig. 1 convergence is achieved by inclining right duct wall which partially directs gas flow toward upper left corner of separator domain. It can be also seen that shortest flow route that links corner with separator outlet passes through cross-section between flap S14 and upper S13 flap. In addition to that, only portion of gas-flow passing between these two flaps is brought in the vicinity of outlet cross-section while other mid-passes between flaps firstly direct gas-flow toward separators volume where gas phase velocity is significantly reduced which can be considered as additional hydraulic loss. Finally, slope of vertical duct ceiling enhance portion of gas-flow brought to the upper left corner of separator to be guided through area between S14 and upper S13 flap.

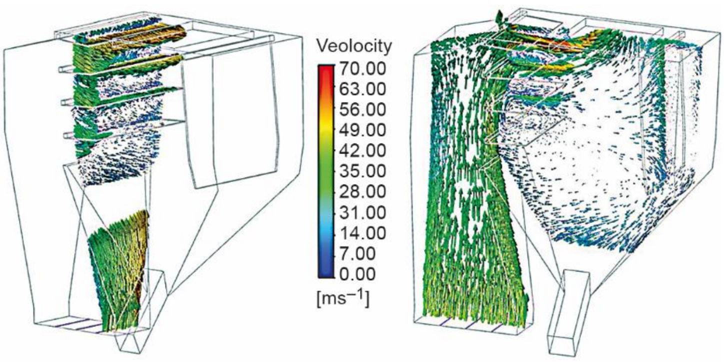

Figure 4. Velocity field in characteristic cross-sections

Results and discussion

After validitng calculation model acc. to the results given in both columns of tab. 1 for referent positions of all regulating flaps CFD calculations for different flaps positions have been conducted. Inertial separator performances have been investigated when S13 flaps are rotated for +20º, +10º, –10º, and –20º with respect to horizontal plane. Influence of S14 flap has been assessed when flap takes two following positions: when flap is rotated toward inertial separator ceiling, as much as geometry of ceiling, position of rotating shaft and flap length allows, and when flap is rotated for –9º with respect to horizontal plane. The S12 flap is, during validation of calculation model, rotated toward back wall of inertial separator (referent case), while its influence is considered when rotated for +20º and + 30º with respect to the vertical plane. All analyzed positions of regulating flaps along with their position in referent case are given in fig. 5. When one group of flaps is rotated others remain at referent case position.

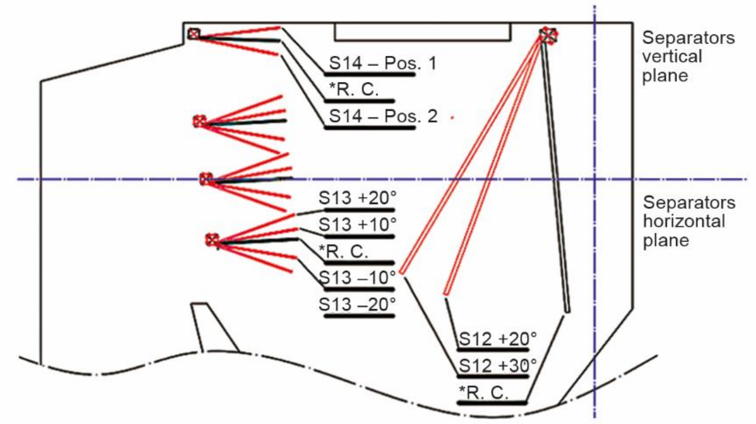

Figure 5. Analyzed positions of all regulating flaps; *R. C. – referent case*

Changing position of regulating flaps

Influence of changing positions of all regulating flaps on milling capacity (coal mass flow at separators outlet) and residue on 90 µm sieve for different values of solid phase specific weight (1080 kg/m^3, 1280 kg/m^3, 1480 kg/m^3, and 1680 kg/m^3) is shown in figs. 6 and 7.

By rotating flap S13 upward two phase mixture is guided toward separators outlet. In such arrangement solid phase mass-flow through separators outlet increases and for case when S13 flaps are at +20º to the horizontal plane milling capacity reaches maximum value, fig. 6(b). Although more solid particles leave the separator, increase is mainly achieved by enlarging portion of larger coal particles, fig. 7(b). Consequently, value of R_{90} also reaches maximum at top-raised position of S13 regulating flaps which gives reduced fineness of grinding at outlet cross-section. As flaps are being rotated in opposite direction, gas phase velocity vector in flaps area is being directed toward separators volume (referent case) and, further, toward bottom of separators hopper. As gas phase velocity vector participates in defining particle inertia force, when flaps S13 are rotated downward, larger portion of particles is sent to the separator volume or directed toward separator hopper. In that case, as larger particles are more inert, it is to expect that smaller portion of these particle groups passes through separators outlet cross-section leaving larger portion of smaller particles in outlet mill gaseous mixture, thus, increasing fineness of grinding in separators outlet, as it is shown in fig. 7(b). In addition to that, smaller ammount of larger particles at outlet cross-section implies reduced milling capacity, as shown in fig. 6.

Taking in consideration particles trajectory in fig. 9 it is to be stated that particles move from inlet section toward ceiling, collide with ceiling, rebounce and sharply turn toward flap region. Still, most of particles move relatively near ceiling where flap S14 is located. Turning this flap from ceiling to the referent position, fig. 5, not significant change occurs in both, milling capacity, fig. 6(c) and fineness of grinding, fig. 7(c), of outgoing pulverized coal. If the flap is rotated at position –9º in respect to the horizontal plane milling capacity is to be reduced significantly while fineness of grinding is to be increased. This position disturbs

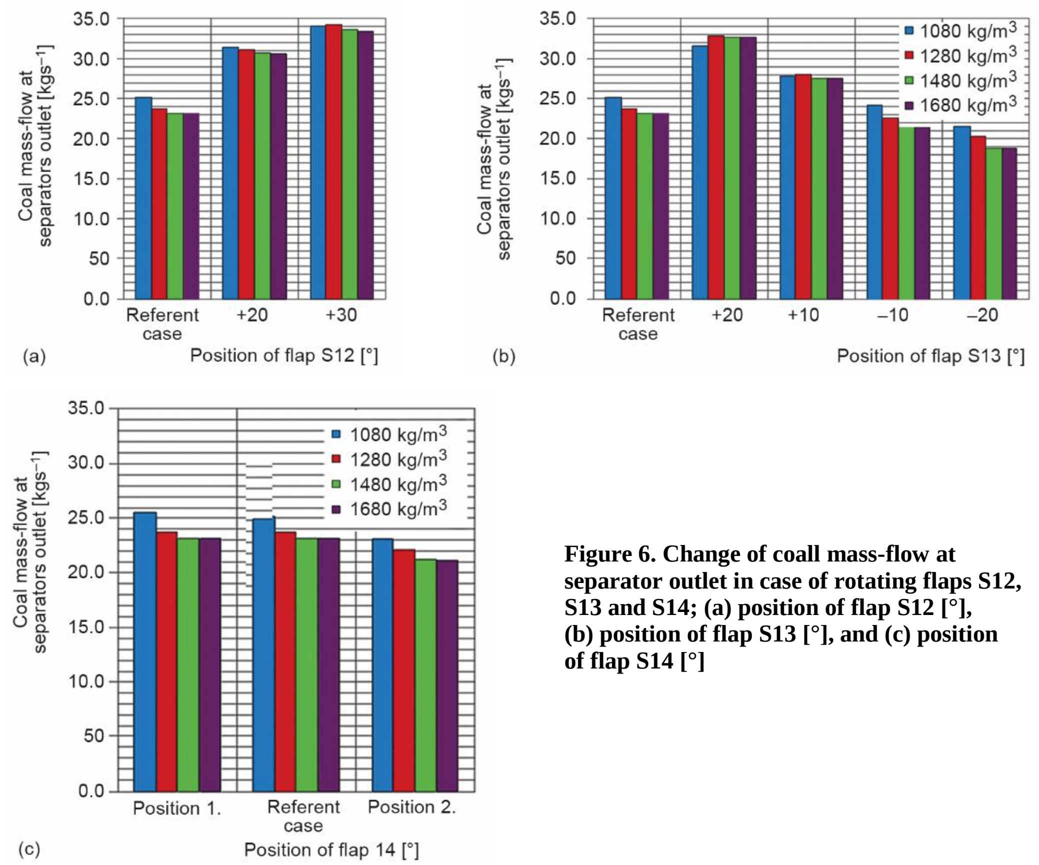

Figure 6. Change of coall mass-flow at separator outlet in case of rotating flaps S12, S13 and S14; (a) position of flap S12 [°], (b) position of flap S13 [°], and (c) position of flap S14 [°]

flow more intensively in comparison when this flap is aligned to the horizontal plane or rotated toward ceiling and, consequently, forces gas and solid phase flow in the vicinity of the flap to start moving toward hopper. After such impact resultant particle inertia force drags larger particle portions toward separators hopper leaving larger portion of smaller particles in reduced solid phase outlet mass-flow.

Flap S12, in its flat-plane construction and position, when rotated, reduces separation volume and directs gas phase flow toward separators outlet. If flap S12 is rotated for +20º to the vertical plane, or even more (+30º), larger particles passing S13 flap region collide with flap S12, and, due to its rotated position, are being directed toward separator outlet. Otherwise, if flap S12 would be positioned as in referent case, larger particles would pass in front of outlet cross-section and after collision with S12 flap they would fall into separator hopper and return to the mill for additional grinding. Consequently, when flap S12 is rotated toward separators volume, increase in milling capacity, fig. 6(a) is followed by increase in R_{90}, fig. 7(a) in pulverized coal.

In diagrams on figs. 6 and 7 for every analized flap position changes of milling capacity and R_{90} in dependence of solid phase specific weight is shown. It can be stated that increase of particles specific weight decreases milling capacity as well as R_{90} of pulverized coal. As stated in section *Mathematical modeling* specific weight of solid phase influences intensity of drag and gravitational force which are of crucial importance in determining solid

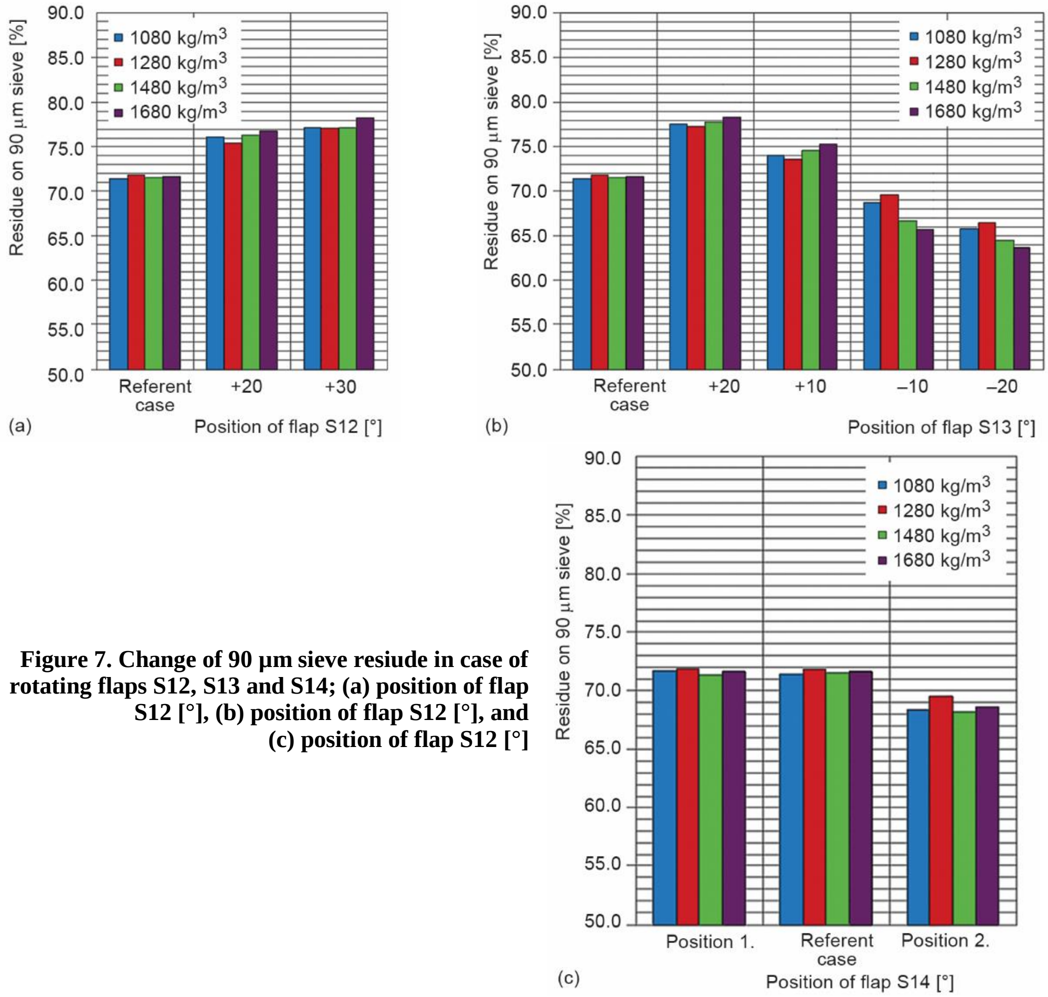

Figure 7. Change of 90 μm sieve resiude in case of rotating flaps S12, S13 and S14; (a) position of flap S12 [°], (b) position of flap S12 [°], and (c) position of flap S12 [°]

phase trajectories. *Heavier* particles are more inert which requires heigher intensity forces to provoke changes in final shape of their trajectories. For these particles gravitational force intensity is heigher and in conjuction with lower gas phase velocity in separators volume resultant force drags larger portion of particles toward separators hopper. Contrary to that, *lighter* particles are easily carried by gas phase flow and, in acc. to that, larger portion of solid phase is guided toward separators outlet giving increase of milling capacity to certain extent. However, although variation in solid phase specific weight has influence on milling capacity, its influence is not of significant importance. Heighest differences are notable between specific weight values of 1080 and 1680 kg/m^3 for any position of regulating flaps and do not overcome value of 10% in milling capacity.

Also, it is to be stated that although change in solid phase specific weight has certain influence on milling capacity, it almost does not affect fineness of grinding of pulverized coal at separators outlet. This is clearly shown in fig. 7. Changes of R_{90} is not larger than 3% which means that when flaps are rotated increase or decrease of milling capacity is achieved by equal share of larger and smaller particles, that is, by all particle groups.

It is purposeful to note that change in milling capacity and fineness of grinding when varying specific weight of solid particles for some flap positions is not always monotonic non-increasing or non-decreasing function. As particle specific weight influence drag force as well as gravitational force it can be considered that common influence of these two forces is not of monotonic character. Such occurrence might be seen in fig. 7(b) for –10º and –20º S13 flaps position.

Changing recirculation rate of inertial separator

Gas phase flow of mill gaseous mixture enters the separators volume, and after passing flaps region, splits on two parts. Larger part of mixture leaves separator through outlet cross-section while smaller part is returned to the mill impeller *via* recirculation duct. In fig. 2 it is notable that geometry of separators hopper and recirculation duct is such to provide as less as possible gas phase to be returned to the mill impeller. However, if additional flap inside recirculation duct would be placed additional possibility for regulating mills performance would be provided. Such arrangement would allow direct control over portion of gas phase mass flow which is returned to mill impeller as well as gas mass flow leaving separator through outlet section. During validation of calculation model distribution of inlet gas phase mass flow at outlet cross-sections was set in order 85-15%. To additionally investigate possibility to increase milling capacity calculations for referent case of all flaps position and gas phase flow distribution of 90-10% and 95-5% have been performed. Results of these calculations are shown in fig. 8.

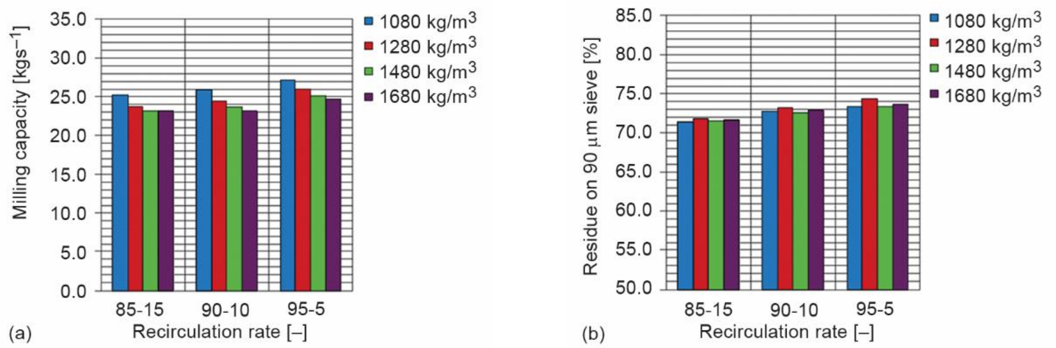

Figure 8. Change of milling capacity and 90 μm sieve resiude for different recirculation rates in inertial separator

Increasing gas phase flow leaving separator through outlet cross-section at same value of inlet mass-flow unavoidably increase velocity magnitude of gas phase in the vicinity of separators outlet which ensures higher solid phase mass loading of carrier fluid (gas phase carrying cappabilites) in this region to be achieved. Such expectance is to be confirmed in figs. 8(a) and 8(b). By reducing recirculation rate milling capacity and R_{90} grows. However, maximum difference in final result is relativelly small – increase in milling capacity when changing recirculation rate from 85-15 to 95-5 is not larger then 5%. Such modest change comes from the fact that recirculation rate has been adjusted in narrow range. Increase of outgoing gas phase mass-flow for 5% or even 10% provides increase of gas phase velocity magnitude at the same rate which gives low intensty changes on outgoing solid phase mass flow.

Comparing gas phase streamlines with particles trajectories

In fig. 9 gas phase streamlines as well as three different-sized particles trajectories are shown. Both streamlines and trajectories are released from inlet Section II and III and their number and density has been reduced.

Inlet velocity of gas phase, as it can be seen in fig. 4 is larger than 40 m/s. Maximum values are achieved in area between flap S14 and S13 upper flap and in recirculation duct (due to its reduced cross-section).

Figure 9. Comparative overview of gas phase streamlines and trajectories of different-sized particles

As particles trajectories are determined by the influence of forces transferred from gas phase, their movement is not of similar character when different-sized particles are analyzed. In fig. 9 trajectories of particles of 0.05 mm (blue line), 0.18 mm (turquoise line), and 0.6 mm (red line) is shown. As it can be seen, smallest particles trajectories show high resemblance rate to the gas phase streamlines. Such behavior comes from small volume and mass of the particle and potentially low intensity of its inertia force. Particles of 0.18 mm diameter are more inert and, although they are injected into calculation domain with same velocity magnitude as smaller particles, they approach to the separator ceiling and in the vicinity of ceiling turn toward flap region. While trajectories of these two group of particles follow gas phase streamlines to the certain extent significant deviation in shapes of 0.6 mm particle trajectory and gas phase streamline is to be detected. Inertia of this particle defined by its mass and injected velocity cause collision between particle and separator ceiling, After collision kinetic energy of particle is significantly reduced and its further movement is defined by the surrounding fluid flow configuration moving this particle further in region between flap S14 and upper S13 flap. Current position of these flaps defines velocity vector of particle at the entrance of separators volume and, if they are directed toward outlet cross-section particle will, eventually, leave inertial separator and continue to move toward boilers furnace. If they are rotated toward separators hopper particle will be guided to the separator recirculation duct. Thus, it can be concluded that particles of 0.6 mm diameter and larger are sufficiently inert so their overall movement is strongly influenced by current positions of all flaps in inertial separator.

Conclusion

In this paper results of calculations of two phase flow in inertial separator of coal dust at TPP Nikola Tesla Unit B have been presented. Geometry of separator used in calculations is identical to the real scale facility.

Calculations has been performed by use of CFD methodology. For the purpose of applying boundary conditions measurements taken on site along with heat balance calculations of milling plant have been used. Distribution of groups of particles in inlet cross-section has been determined iteratively to obtain CFD calculations results close to the values given in tab. 1.

In order to determine performance of inertial separator CFD calculations has been performed for different positions of all regulating flaps, different values of recirculation rates and different values of specific weight of solid phase.

Calculation results showed that changes in solid phase specific weight does not affect milling capacity nor fineness of grinding of pulverized coal at separators outlet significantly. Largest difference in milling capacity at the same flaps positions occurs when comparing cases with solid phase specific weight of 1080 kg/m^3 and 1680 kg/m^3 and it does not overcome value of 10%.

Calculations also confirmed that adjusting recirculation rates in range from 85-15% up to 95-5% gives somewhat increase in milling capacity and residue on 90 μm sieve which is at best not larger than 5%.

Most influential to the inertial separator and overall milling plant performance are positions of all regulating flaps. Rotating S12 and S13 flaps toward separators outlet milling capacity can be enlarged for almost 25% (when comparing results with referent case flap positions). However, such increase is followed by drastic deterioration of fineness of grinding of solid phase and for this positions R_{90} goes from cca. 70% in referent case to the 78% in top-raised S13 and S12 flap positions. Since design value equals R_{90} = 65% such higher values will eventually have negative impact on the efficiency of combustion process in boilers furnace.

When S13 flaps rotate toward hopper milling capacity is reduced while fineness of grinding is improved in comparison to the referent case flaps position.

When flap S14 is pointed toward ceiling or directed to the left edge of separators collar, its influence on separators operational parameters is minor. This flap have larger impact on separators performance when it is rotated from pointing left edge of separators collar further toward separators hopper (for ex. position –9° with respect to the horizontal plan). In these positions top of flap strongly influences direction of velocity vector of both phases entering separators volume which is, in conjunction with solid phase inertia, of decisive importance for separation process obtained in separators volume. When rotated downward milling capacity reduces significantly in comparison to the referent case while R_{90} is decreased as shown in fig. 7(b).

Inertia of different-sized particles to the gas phase flow can be observed in fig. 9. It is shown that double turn of gas phase in separator volume for only 0.4 seconds ensures only smallest particles to closely follow gas phase streamlines (particles with diameter below 0.1 mm). Trajectories of all larger groups deviate significantly from gas phase streamlines and their movement is strongly influence by collision with separators flow boundaries and current positions of all regulating flaps.

In order to get closer to the process occurred in mill impeller and to examine geometry of impact of solid phase on mill impacting planes next stage of research will be dedicated to analyzing character of two phase flow in mill impeller.

Acknowledgment

This work has been supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Project: Modern approach to improvement process in existing steam boilers in order to increase energy and environmental efficiency, No. contract: 451-03-68/2022 – 14/200105).

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Paper submitted: July 7, 2022
Paper revised: December 28, 2022
Paper accepted: December 30, 2022
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