

POSSIBILITIES FOR INCREASING EFFICIENCY OF MILLING PLANT OPERATION FOR THE PURPOSE OF OPTIMIZING COMBUSTION PROCESS WITHIN POWER STEAM BOILER

by

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During retrofits taken on power unit "Nikola Tesla" A6 in 2011 for the purpose of increasing its overall production capacity certain modifications on milling plants have been applied. Enlargement of power steam boiler production capacities included increase in milling plant output with existing number of mills in operation. Changes made on arrangement of pulverized coal burners, geometry of mill gaseous mixture distribution elements inside mill gaseous mixture duct as well as operational rotational speed of mill impeller led to increase of milling capacity to the certain extent. Consequently, applied modifications resulted in higher primary air-flow required for the purpose of regulating mill gaseous mixture temperature, thus, reducing secondary airflow in burners below recommended level which affected combustion process within boiler furnace. In this paper results of thermal calculations of power steam boiler and aerodynamic calculations of milling plant for the present operating conditions have been presented. Calculations results have been validated by use of measurements taken on site in present operating conditions. Impact on overall boiler operation made by modifications taken on milling plants has been discussed in details. In text new measures, which would reduce occurred negative effects, have been proposed. Positive effects of proposed measures, as new operating point of milling plant, are confirmed by the results of additionally performed thermal and aerodynamic calculations given in this paper.

Key words: *milling plant, lignite combustion, coal milling, aerodynamic calculation*

Introduction

For the purpose of maintaining stable and optimal combustion process within boilers furnace low calorific coal, lignite, is to be introduced into milling plant where raw particles are submitted to drying and milling processes [1]. As a result of these simultaneous processes coal dust of significantly reduced median diameter and lower moisture content leaves milling plant. When milled and dried accordingly small coal particles introduced to the furnace burner zone [2] require less time for complete evaporation of remained water content which ensures earlier start of devolatilization stage and initial combustion.

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As stated in [3] milling plants operated in thermal power plants are designed on the basis of predefined properties of coal predicted to be utilized for producing superheated steam in high pressure power steam boilers. Some of important coal properties for the design of milling plants are its lower/higher heating value, water content, certain mechanical properties (for ex. grindability affinity) as well as overall coal consumption at maximum steam production rates.

It is widely accepted [4] that geologically younger coals characterized by larger portions of moisture content and volatiles matter are successfully milled and dried in milling plants supplied with fan mills. This type of mills is suitable for milling and drying of lignite for two main reasons – first, impact milling that occurs on fan mill plates reduces median diameter of coal to the required extent and second, its fan alike construction provides sufficient drying agent mass-flow rate required for adequate drying of coal particles within milling plant.

Typical simplified scheme of milling plant with closed coal drying loop is shown in [3]. For the purpose of drying and carrying of solid phase re-circulated hot gases at furnace outlet are brought to mill while pre-heated primary air is dosed for the purpose of regulating mill gaseous mixture temperature at mill outlet. As mills are regarded as solid fuel *feeder* of the large-scale steam boilers their optimal operation is of crucial importance for stable operation of boilers plants. Reduced mill performances might lead to the increase in unburnt content in slag and ash [5] as well as higher nitrogen oxides emissions at the furnace outlet [6] which directly affects steam boilers efficiency and ecological performances.

As processes in mills are very complex and, thus, even nowadays analytically unresolved, existing construction are designed by use of mathematical models obtained on the basis of semi-empirical/experimental data. This is the case with well-known and widely accepted formula for calculating maximum milling capacity of fan mill given in [7] originally provided by CBTI (Central Boiler and Turbine Institute, St. Petersburg, Russia):

$$B_{\max} = \frac{k_1 k_2 n^2 D_1^3 b (0.0034 k_H^{1.25} + 0.61) k_3 k_4}{\left(\frac{R_{5000}}{20}\right)^m \left(\ln \frac{100}{R_{90}}\right)^{0.5}} \quad (1)$$

where B_{\max} [kgs⁻¹] is the maximum milling capacity, k_1 [-] – the coefficient that depends on type of coal and type of milling process, k_2 [-] – the mill impeller wear coefficient, n [s⁻¹] – the rotational speed, D_1 [m] – the mill impeller outer diameter, b [m] – the width of mill impact plates, k_H [-] – the coal Hardgrove grindability coefficient, k_3 [-] – the coefficient of coal dust water content, k_4 [-] – the coefficient of coal water content, R_{5000} [%] – the coal residue on sieve of 5.0 mm, R_{90} [%] – the coal dust residue on sieve of 0.09 mm, and m [-] – the coal sort exponent.

Second formula obtained by using the same empirical approach is given in Effenberg [8]:

$$\dot{m}_{Btr} = CM_{Ha} \left(\ln \frac{100}{R_{90}}\right)^{-0.5} D_a B_i \quad (2)$$

where \dot{m}_{Btr} [th⁻¹] is the maximum milling capacity, C [-] – the coefficient that depends outlet tangential speed of mill impeller, M_{Ha} [-] – the coal Hardgrove grindability coefficient, D_a [m] – the mill impeller outer diameter, B_i [m] – the width of mill impact plates, and R_{90} [%] – the coal dust residue on sieve of 0.09 mm

Additional sub models of second formula in which influence of coal maceral composition on overall milling capacity is elaborated can be found in Obradović [9].

Although shown equations are used in many cases in designing fan mills or predicting milling plants performances, not all functional mathematical correlations between parameters on the right hand side are established. For instance, fineness of grinding, R_{90} , in eqs. (1) and (2) represent input data, while it might be correlated with mechanical properties of coal and tangential velocity of mill impeller calculated at impeller outer diameter.

Simple observing of the parameters on the right side of eqs. (1) and (2) might lead to the conclusion that increase in rotational speed or outer impeller diameter will unavoidably result in increase of maximum milling capacity, when values of R_{90} and R_{5000} and its grindability coefficient are kept the same. However, such straightforward approach is restrictive in predicting operational performances of furnace-milling plant feedback system. In some cases, conclusions brought on the basis of simplified parametric analysis of eqs. (1) and (2) might lead to the contrary effects and reduce operational capacities of the coupled furnace-milling plant system.

In this paper negative effects of change in mill rotational speed in milling plant at thermal power plant *Nikola Tesla* Unit A6 are shown. By use of thermal and aerodynamic calculations of milling plant and power steam boiler as a whole new measures for increasing degraded performances are provided.

Case study

Coal preparation system at TPP *Nikola Tesla* Unit A6 arranged according to the closed coal drying loop scheme with direct blowing of coal dust to the furnace is supplied with fan mills. Drying of coal is performed by recirculated hot gases at furnace outlet while primary air is utilized for regulating mill gaseous mixture temperature at plants outlet. Main steam boiler design parameters are given in tab. 1, while design parameters for fan mill N270.45 from [10] are given in tab. 2.

Table 1. Boiler design parameters

Nominal steam production	\dot{m}_{ST}	255.56	kg/s
Superheated steam pressure	p_{ST}	18.3	MPa
Superheated steam temperature	t_{ST}	543	°C
Nominal reheated steam production	\dot{m}_{RH}	228.78	kg/s
Reheated steam pressure	p_{RH}	4.2	MPa
Reheated steam temperature	t_{RH}	543	°C
Reheated steam pressure at boilers inlet	p_{CRH}	4.5	MPa
Reheated steam temp. at boilers inlet	t_{CRH}	333	°C
Feedwater pressure	p_{FW}	21.3	MPa
Feedwater temperature	t_{FW}	248	°C

Table 2. Fan mill design parameters

Mill designation	EVT - N 270.45
Maximum milling capacity	25.83 kg/s (93 t per hours)
Nominal milling capacity (guaranteed coal)	23.61 kg/s (85 t per hours)
Rated ventilation for nominal milling capacity	205000 Nm ³ /h
Rotational speed of mil impeller	420-480 (490) ^o per minutes
Mill gaseous mixture temperature	180 °C
Mill impeller outer diameter	3600 mm
Mill impeller inner diameter	2388 mm
Width of mil impeller impact plates	990 mm
Number of impact plates	12

Design layout of coal preparation plant is presented on fig. 1 on the left. When mill is in operation hot recirculated gases at furnace outlet are brought to the re-circulation head – 1. Here, primary air is introduced to the milling plant by air channel – 2. Drying agent, that is, mixture of these two fluids is further guided downward to the fan mill. Raw coal particles are

injected into drying agent stream by connection – 3. When injected, particles are being dried and, further, introduced to the mill impeller spiral housing – 4 where grinding is performed. After mill, solid-gaseous mixture is guided toward inertial separator – 5 where larger particles are separated from mill gaseous mixture stream and returned to the mill impeller entrance zone for regrinding. Rest of the mill gaseous mixture is brought to the coal dust burners arranged in five stages, where three – 6 of six are grouped and located at the lower burner zone while the rest – 7 are placed in the upper burner zone.

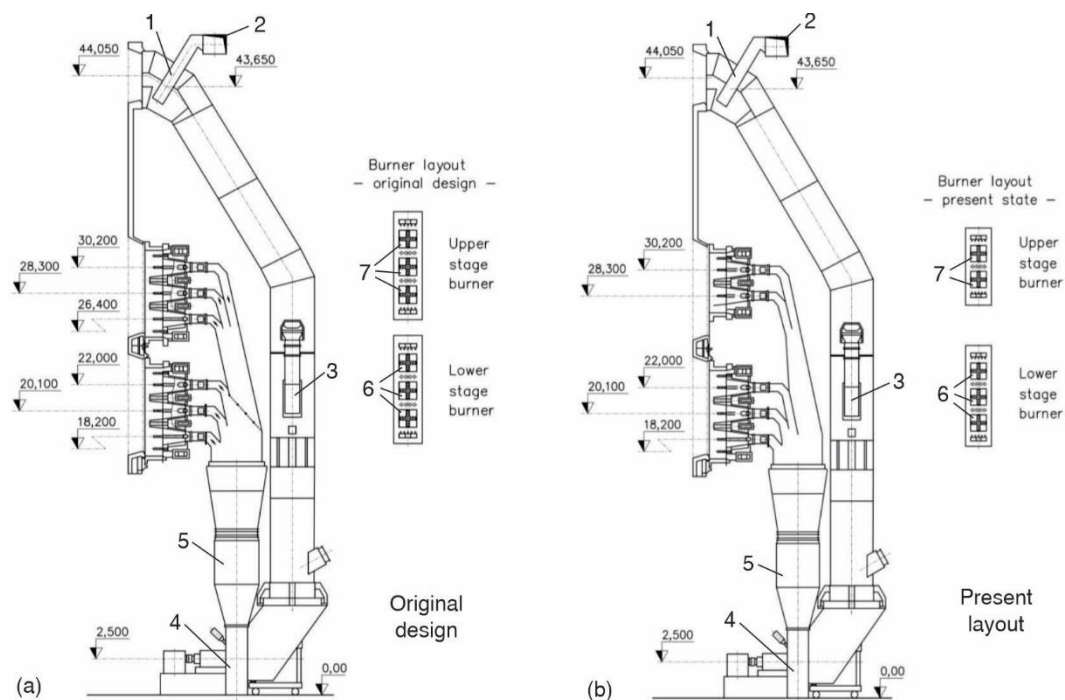


Figure 1. Coal preparation plant at TPP Nikola Tesla A6 with burners layout before (a) and after modification (b)

During second half of first decade of 20th century numerous projects and studies [11] were performed for the purpose of analyzing possibilities for enlarging TPP *Nikola Tesla A6* overall unit capacity. Increase in unit output power, amongst other, implied performing certain retrofits on milling plants for the purpose of increasing maximum milling capacity at the condition of retaining all other operational quality parameters.

In several passes, milling plants were reconstructed such that bottom mill gaseous mixture burner nozzle of upper burner stage was eliminated along with all obstacles (moving flaps, mill gaseous mixture distributors, *etc.*) within mill gaseous mixture duct. Additionally, increase in rotational speed of mill impeller was applied by replacing existing hydraulic couplings in impeller momentum supply facility. The aim was to increase drying agent mass-flow and increase impact effect on raw coal particles, which would, as an overall effect, eventually lead to the increase in milling capacity. In first iteration rotational speed was increased to the level of 490° per minutes, and, afterwards, even to the 530° per minutes. This value is kept up to now and adopted as new nominal value.

Present performances of furnace-milling plant facility

After applying changes on milling plants, measurements have been taken for the purpose of monitoring new operational parameters. Reduced overview of the results from reports of performed measurements done during 2019th and 2023th [12, 13] are given in tab. 3.

Table 3. Milling plant measurement and thermal and aerodynamic calculation results

No.	Measured parameter	Unit	Value			
			Mill no. 65 20.03.2019.	Mill no. 61 20.03.2019.	Mill no. 61 27.03.2023.	Results of thermal and aerodynamic calculations
1	2	3	4	5	6	7
1.	Rotational speed	°/min	529	527	526	526
2.	Primary air-flow	Nm ³ /h	–	–	97770.0	97743.0
3.	Air-flow per milling plant	Nm ³ /h	107000.0	126000.0	131800.0	131879.0
4.	Milling capacity – sampling on coal dust side	t/h	114.35	87.83	106.44	98.211
5.	Milling capacity – by coal feeder geometry	t/h	90.85	80.35	95.77	
6.	Water content in coal dust	%	13.7	10.7	18.9	18.75
7.	Mill ventilation	Nm ³ /h	267620.0	248119.0	251744.0	251823.0
8.	Residue on sieve R1000	%	7.06	7.34	9.68	9.68
9.	Residue on sieve R90	%	55.64	53.43	69.85	69.85
10.	Mill gaseous mixture temperature	°C	196	205	186	186
11.	Time in operation	h	330	2728	1000	–
12.	Coal water content	%	46.2	50.3	50.7	50.7
13.	Coal mineral matter content	%	20.3	20.4	13.3	13.3
14.	Coal lower heating value	kJ/kg	7186.0	5894.0	8014.0	8014.0
15.	Area-averaged secondary air velocity at burner outlet	m/s	–	–	–	9.89
16.	Area-averaged mill gaseous mixture velocity at burner outlet	m/s	–	–	–	30.83

When comparing data from tab. 3 and design mill parameters from tab. 1 it can be stated that increase in mill rotational speed resulted in increase of milling capacity (tab. 3, line 5). Reduced milling capacity for mill no. 61 (tab. 3, column 5) is consequence of mill operation at the end of its working cycle (≈3000 hours), that is, high wear of its working elements.

Fineness of grinding of coal dust sampled during 2019th is also improved (tab. 3, lines 9 and 10) which is expected due to increased impact effect of mill rotating plates on incoming coal particles. Decrease in fineness of grinding for mill no. 61 (tab. 3, column 6) can be explained by instantaneous deterioration of grinding Hardgrove coefficient of raw coal during testing.

Also, significantly higher fan mill ventilation is notable in all given cases (tab. 3, line 7), regardless of wearing state of mill, coal quality and milling capacity. In line with that, primary air-flow is also increased such that value is several times larger than secondary air-flow guided to the coal dust burners in furnace.

As it is stated in [14] optimized combustion of solid fuel might be achieved when, amongst the others, ratio of air/fuel injecting velocities are kept in certain range. In case of burning lignite, this range goes from (at least) 2.0 to 3.0. Upper values are preferred in case of

sub stoichiometric combustion [15], which is the case when primary de-NO_x measure is applied. In order to check overall performance of milling plant-furnace facility, thermal calculations of power steam boiler at TPP *Nikola Tesla A* Unit 6 are performed.

Mathematical model given in [2] used for performing calculations is calibrated against measurement results of boiler and milling plant operational parameters performed on 27.03.2023. Reduced overview of measurements and results of thermal calculations of entire power steam boiler are given in tab. 4 (columns 4 and 5) while results of thermal and aerodynamic calculation of milling plant are given in column 7 of tab. 2. All calculation results are close to the measured values with exception of furnace outlet flue gas temperature which is expected since temperature measuring probes are mounted on the furnace walls with relatively small penetration depth into flue gas channel while calculated value is area-averaged and, thus, higher from measured one.

Table 4. Boiler plant measurement and thermal calculation results

No.	Parameter	Unit	Value	
			Measurement data	Results of thermal calculations
<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>
1.	Date	–	27.03.2023	–
2.	Measurement duration	HH : MM	14:25 - 15:39	–
3.	Electrical output of the unit	MW	282	282
4.	Superheated steam flow	t/h	795	795
5.	Superheated steam pressure	bar	152	152
6.	Superheated steam temperature	°C	534/533	533
7.	Reheated steam pressure	bar	30/30	30
8.	Reheated steam temperature	°C	538/537	538
9.	Reheated inlet steam temperature	°C	325	325
10.	Feedwater pressure	bar	171	171
11.	Feedwater temperature	°C	178	178
12.	Injection in desuperheaters	t/h	150	150
14.	Hot air-flow	Nm ³ /h	656000.0	672857.0
15.	Air temperature at air-preheater inlet	°C	40/40	40
16.	Air temperature at air-preheater outlet	°C	249/249	251
17.	Flue gas temperature at air-preheater inlet	°C	265/264	265
18.	Flue gas temperature at air-preheater outlet	°C	155/147	151
19.	O ₂ content in flue gas at air-preheater inlet	%	3.53	3.53
20.	Coal consumption	t/h	372	367
21.	Boiler efficiency rate	%	–	84.2
22.	Flue gas temperature at furnace outlet	°C	867/946	1002
23.	Number of mills in operation	–	5	5

After performing previously described modifications on milling plant higher values of fan mill ventilation occurred. In order to maintain mill gaseous mixture outlet temperature, beside increased feeding of the raw coal to the plant, higher quantities of primary air are required. When primary air-flow is increased, for the purpose of retaining value of excess air coefficient at the furnace outlet, secondary airflow is reduced which led to decreasing of secondary air velocity at burner outlet. Moving secondary air/mill gaseous mixture injecting

velocity ratio outside optimal range influenced kinetics of combustion process in furnace. Momentum of secondary air jet is reduced and insufficient for appropriate dosing of oxygen into core of swirl in furnace formed by coal dust burners placed in tangential arrangement. Consequently, combustion process is postponed resulting in increase of furnace outlet flue gas temperature. This effect provided additional increase in primary airflow for the purpose of retaining mill gaseous mixture temperature in predefined range (below 200 °C).

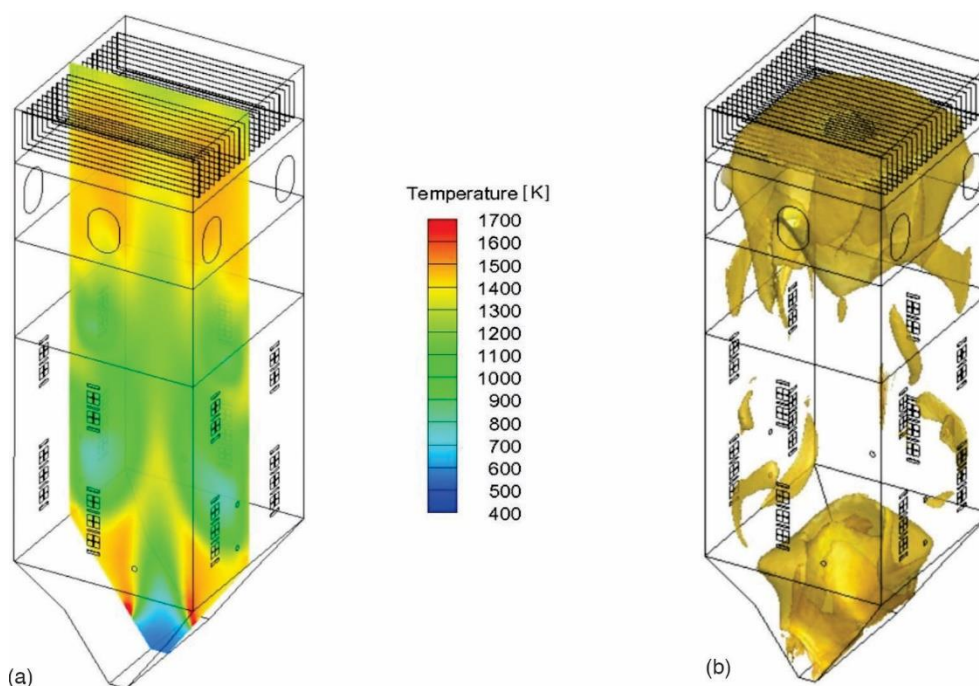


Figure 2. Temperature field in furnace for power steam boiler at TPP Nikola Tesla A Unit 6 at present state (non-optimized secondary air/mill gaseous mixture velocity ratio)

Heat transferred on superheaters in convective part of gas channel depends on temperature of flue gas leaving the furnace, and, in case of its increase, it grows which can provoke higher mass-flow of feedwater into desuperheaters. This mass-flow for the observed operation regime of power steam boiler is at rate of almost 20% (cca. 150 t per hours) to the superheated steam production (795 t per hours) which might be a consequence of postponed combustion in furnace due to the non-optimized secondary air/mill gaseous mixture velocity at burner outlet.

To additionally confirm this statement CFD calculations of processes within furnace were performed. The CFD calculations are performed entirely according to the model given in [16]. In fig. 2(a) temperature field in longitudinal furnace cross section is shown while isotemperature contours for the same calculation domain are given in fig. 2(b). For the purpose of visual comparison with case when combustion is optimized on fig. 3 results of CFD calculation of the processes within lignite-fired furnace of 350 MWel power steam boiler with optimal secondary air/mill gaseous mixture velocity ratio are shown. As it can be seen on fig. 2(a) zones with higher flue gas temperatures are completely out of the burners zone. Combustion of coal particles mainly occurs in the furnace hopper (burning coal injected via lower stage burner) and in the upper furnace zone (burning coal injected via upper stage burner) while its intensity in

burners zone is significantly reduced. Consequently, volumes of flue gas at temperature higher than 1400 K are located below burners zone and in the vicinity of furnace outlet as it is shown on fig. 2(a). Contrary to that, when combustion process is optimized flue gas high temperature zones are formed in burner zone, fig. 3(a). Transformation of fuel chemical into flue gas heat energy occurs in the lower part of furnace while flue gases are being cooled along furnace height due to the radiation heat transfer toward furnace walls. Thus, flame core can be detected in front of burners outlet cross section as it is shown in fig. 3(b).

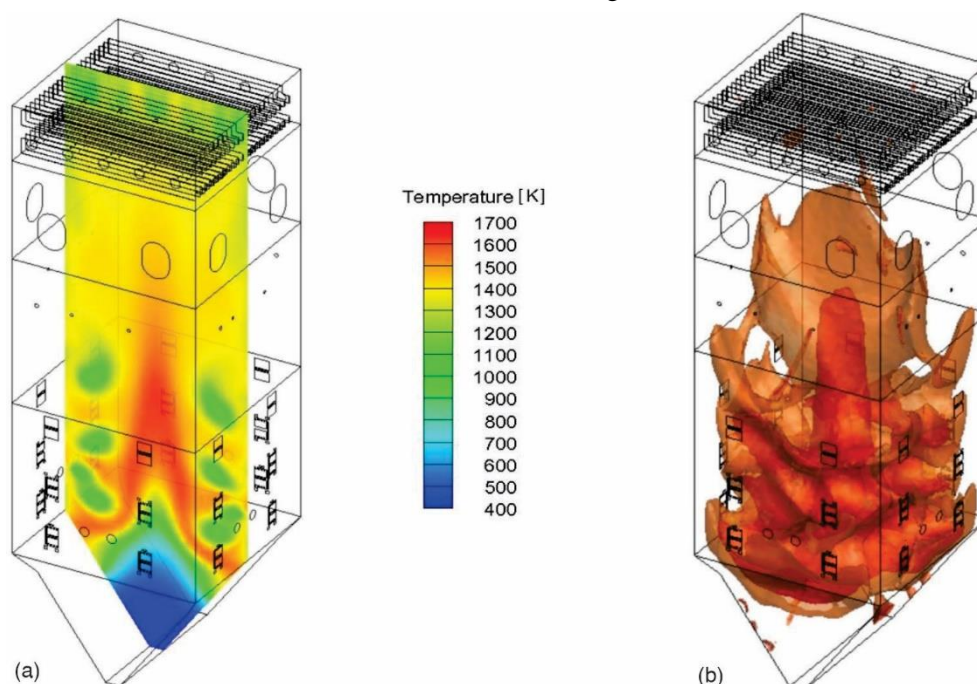


Figure 3. Temperature field in furnace for power steam boiler of 350 MW nominal unit output and optimized secondary air/mill gaseous mixture velocity ratio

Occurred disturbances in combustion process due to the non-optimized secondary air/mill gaseous mixture velocity ratio certainly reduces potential of furnace to mitigate negative effects in case of sudden changes in inlet fuel quality and maintain stable flame propagation throughout furnace volume.

Also, increase in furnace outlet flue gas temperature resulted in increased desuperheating mass-flow which might further lead to the significantly reduced mass-flow of steam/water in receiver line before desuperheaters and deteriorate cooling process of heat exchanger pipelines with real potential to encounter pipe burst during boiler operation.

Measures for optimizing milling plant operation and combustion process

Increase of mill rotational speed certainly gave results on rising milling capacity to some extent rather provoking some negative effects regarding combustion process within furnace. Increased primary airflow for cooling of milling plant resulted in insufficient secondary airflow and postponed combustion within furnace volume.

In order to retain present rate of milling capacity but to eliminate negative effects of performed modification on milling plant it is recommended to organize cooling of milling plant by use of other available fluid and, thus, partially substitute required amount of primary air. In this way, secondary airflow would be increased which would give more favorable values of secondary air/mill gaseous mixture velocity ratio and bring back the bulk of combustion process to the burner zone.

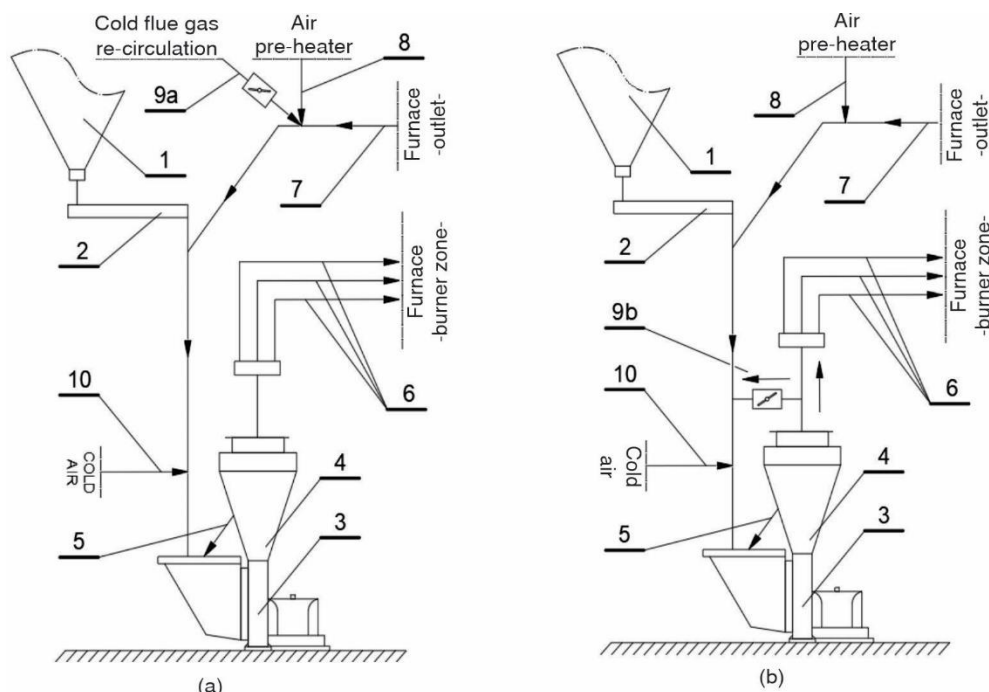


Figure 4. Milling plant scheme with; (a) re-circulation of cold flue gases and (b) local re-circulation of mill gaseous mixture: 1 – coal bunker, 2 – coal feeder, 3 – fan mill, 4 – mill inertial separator, 5 – separator re-circulation, 6 – coal dust burners levels, 7 – re-circulation of hot gases at furnace outlet, 8 – primary air line, 9(a) – re-circulation of mill gaseous mixture, 9(b) – re-circulation of cold flue gases, and 10 – cold air intake

Cooling of milling plant might be performed by recirculated cold flue gases at the boilers outlet according to the scheme given in fig. 4(a). This solution is well known, applied and proven and will, eventually, eliminate detected negative occurrences. For the purpose of analyzing an overall effect of this solution on boiler performances thermal and aerodynamic calculations of boiler and milling plant are performed.

Second, less conventional, approach would be to consider re-circulation of mill gaseous mixture locally, in every milling plant separately, according to the scheme given in fig. 4(b). Thermal and aerodynamic calculations are performed as for presenting overall effect of this measure on entire boiler operation.

Advantages and disadvantages of both solutions are discussed in detail in further chapters. Calculations and adjustment of re-circulation rates are firstly done for the steam production rates given in tab. 4, column 4. In order to observe effects of these measures all the calculation were repeated for nominal steam production rates of considered power steam boiler.

Re-circulation of cold gases at boilers outlet

Effects of re-circulation of cold flue gases are analyzed in cases when re-circulation rate, acc. to definition given in [1], is set at values of 0.1, and 0.2 (regimes *Ia* and *Ila* in tab. 5). Higher values of re-circulation rate lead to the significant increase of flue gas velocity in flue gas duct and, thus, are not considered here. The magnitude of secondary air velocity increase was also observed in case when boiler work with one milling plant in operation less (4 mills, regime *IIIa*) as well as when air leakages in mill and furnace are brought to the recommended value (regime *IVa*). Results of calculation for nominal production steam rates and all previously analyzed measures applied are given in column 8 of tab. 5 (regime *Va*).

Table 5. Re-circulation of cold flue gases – power boiler thermal calculation results

No.	Parameter	Unit	Value				<i>Va</i> Nominal steam production
			Steam production rate – 795 t/h				
			<i>Ia</i> $r_2 = 0.1$	<i>Ila</i> $r_2 = 0.2$	<i>IIIa</i> 4 mills in operation	<i>IVa</i> Reduced air leak	
<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>	<i>6</i>	<i>7</i>	<i>8</i>
3.	Electrical output of the unit	MW	282	282	282	282	–
4.	Superheated steam flow	t/h	795	795	795	795	974
5.	Superheated steam pressure	bar	152	152	152	152	183
6.	Superheated steam temperature	°C	533.5	533.5	533.5	533.5	543
7.	Reheated steam pressure	bar	31.74	31.74	31.74	31.74	45
8.	Reheated steam temperature	°C	538	538	538	538	543
9.	Reheated inlet steam temperature	°C	325	325	325	325	333
10.	Feedwater pressure	bar	171	171	171	171	213
11.	Feedwater temperature	°C	178	178	178	178	178
12.	Injection in desuperheaters	t/h	150.047	142.507	141.350	141.390	107.092
14.	Hot air-flow	Nm ³ /h	636820	598738	598675	759043	941901
15.	Air temperature at air-preheater inlet	°C	40	40	40	40	40
16.	Air temperature at air-preheater outlet	°C	271	288	288	279	295
17.	Flue gas temperature at air-preheater inlet	°C	280	294	294	292	311
18.	Flue gas temperature at air-preheater outlet	°C	174	197	197	178	191
19.	O ₂ content in flue gas at air-preheater inlet	%	3.53	3.53	3.53	3.53	3.53
20.	Coal consumption	t/h	375	384	384	376	463
21.	Flue gas temperature at furnace outlet	°C	976	951	949	955	989
22.	Number of mills in operation	–	5	5	4	4	5
23.	Air leakage in milling plant and boilers furnace	–	0.41	0.41	0.41	0.21	0.21
24.	Boilers efficiency rate	%	82.32	80.49	80.49	82.03	81.71

When cold gas re-circulation applied, flue gas flow through entire boiler as well as flue gas boiler outlet temperature are increasing (line 18, column 4 and 5, tab. 5, fig. 5). As boiler efficiency rate is decreasing coal consumption for the same steam production rate is enlarged (almost for 5% in case when $r_2 = 0.2$ in comparison with present operation as shown in

fig. 6). Hot air-flow is somewhat reduced if concentration of oxygen in flue gas is retained. Also, desuperheating mass-flow is reduced as consequence of decreased flue gas temperature at furnace outlet.

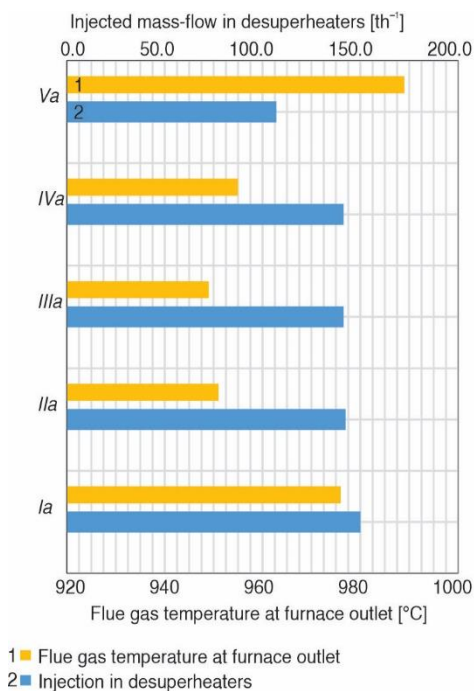


Figure 5. Change of feedwater mass-flow in desuperheaters and flue gas furnace outlet temperature for regimes Ia-Va

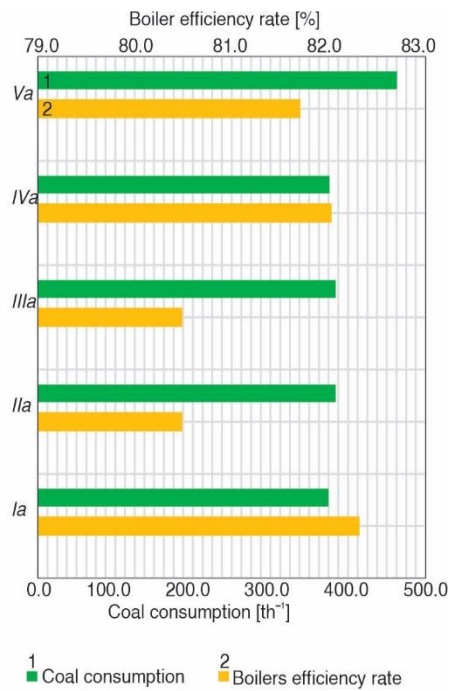


Figure 6. Change of efficiency rate and coal consumption of boiler for regimes Ia-Va

Boiler operation with 4 mills has no effect on overall boiler performance, however it influences operational parameters of milling plant which will be discussed later.

Reduced air leakages in mill and furnace decreases flue gas boiler outlet temperature (from 197 to 178 °C) and provides operation of boiler at higher efficiency rates. This means that boiler might produce same superheated steam mass-flow with lower coal consumption rates and larger flow of hot air coming out of the air preheater.

Boiler work with nominal steam production and all previous applied measures implies 5 milling plants in operation, higher coal consumption rate as well as higher hot air-flow guided from air preheater to the boilers furnace. In case of power steam boiler at TPP *Nikola Tesla* Unit A6, when coal consumption is enlarged desuperheating mass-flow is reduced which is consequence of present ratio of radiative/semi-radiative/convective superheating surfaces. Higher flue gas flow result in increase of flue gas outlet temperature (198 °C) which negatively affect boiler efficiency rate.

Although increase of re-circulation rate certainly reduces overall hot air-flow as well as secondary airflow per milling plant it decreases need for dosing of primary air in re-circulation head providing somewhat increase in secondary air velocity at burners outlet, lines 22 and 23, tab. 5(a). However, this increase is insufficient to obtain optimal secondary air/mill gaseous mixture ratio, as shown in fig. 7. Its value nearly reaches 1.0 when $r_2 = 0.2$ and boiler operates with 4 mills. The value of 1.5 might be obtained only if all proposed measures, including

reduced air leakages in mill and furnace, are applied. For further optimization of this parameter it is necessary to consider boiler operation at higher cold flue gas re-circulation rates (for ex. 0.3). One direction to consider is to reduce mill ventilation not altering its maximum capacity, if possible.

Table 5a. Re-circulation of cold gases – thermal and aerodynamic calculation results of milling plant

No.	Measured parameter	Unit	Value					
			Steam production rate – 795 t/h				Nominal steam production	
			$r_2 = 0.1$	$r_2 = 0.2$	4 mills in operation	Reduced air leakages		
1	2	3	4	5	6	7	8	
1.	Rotational speed	%/min	526	526	526	526	526	526
2.	Primary air-flow	Nm ³ /h	70898	45061	44827	43214	50501	
3.	Air-flow per milling pant	Nm ³ /h	127364	119748	149668	189761	188380	
4.	Milling capacity	t/h	98.212	98.212	98.212	98.212	98.212	
5.	Water content in coal dust	%	18.76	18.76	18.76	18.76	18.76	
6.	Mill ventilation	Nm ³ /h	251830	251830	251830	251830	251830	
7.	Residue on sieve R1000	%	9.68	9.68	9.68	9.68	9.68	
8.	Residue on sieve R90	%	69.85	69.85	69.85	69.85	69.85	
9.	Mill gaseous mixture temperature	°C	186	186	186	186	186	
10.	Raw coal water content	%	50.7	50.7	50.7	50.7	50.7	
12.	Raw coal mineral matter content	%	13.3	13.3	13.3	13.3	13.3	
13.	Raw coal lower heating value	kJ/kg	8014.0	8014.0	8014.0	8014.0	8014.0	
14.	Area-averaged secondary air velocity at burner outlet	m/s	16.24	22.48	31.73	44.20	42.70	
15.	Area-averaged mill gaseous mixture velocity at burner outlet	m/s	30.38	30.38	30.38	30.38	30.38	

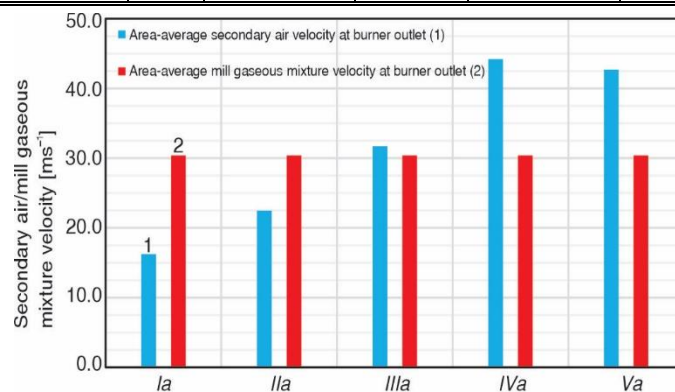


Figure 7. Change of secondary air and mill gaseous mixture velocity at burner outlet for regimes Ia-Va

Re-circulation of mill gaseous mixture within milling plant

Re-circulation of mill gaseous mixture in milling plant is analyzed for re-circulation rates of 0.15 and 0.3 (regimes *Ib* and *I Ib*). As given in previous chapters effects of this measures has been observed when supported with 4 mills in operation (regimes *IIIb*) as well as when air leakages in furnace and mill are decreased (regimes *IVb*). Results of calculation when boiler operates at nominal steam production rates with all measures applied are also provided (regime *Vb*).

This measure, unlike re-circulation of cold flue gases, is applied within control volume of every milling plant. In that case, it has certain effect on milling plant performances as well as on processes within furnace but influence of its change on overall boilers performances is negligible. Thus, boiler operational parameters (efficiency rate, coal consumption, *etc.*) in these analysis depend on considered boiler steam production rate as well as air leakage rate in furnace and milling plant. Therefore, in this chapter table with thermal calculation results of boiler will be not shown. However, change of flue gas outlet temperature, desuperheaters injection, coal consumption and boiler efficiency rate for regimes *Ib-Vb* are given in figs. 8 and 9.

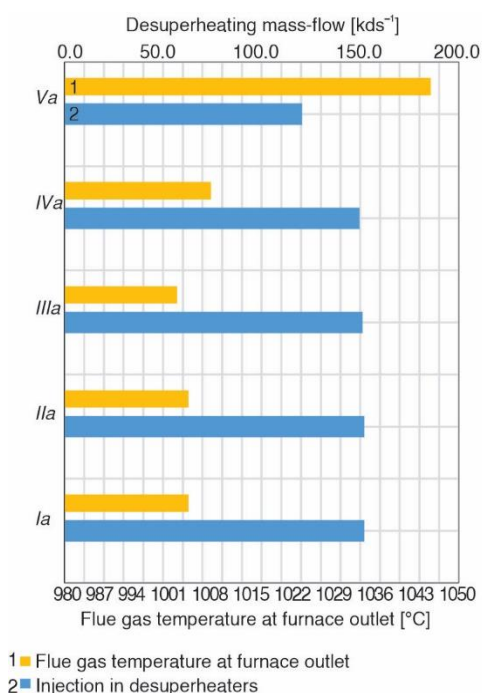


Figure 8. Change of desuperheating mass-flow and flue gas temperature at furnace outlet for regimes *Ib-Vb*

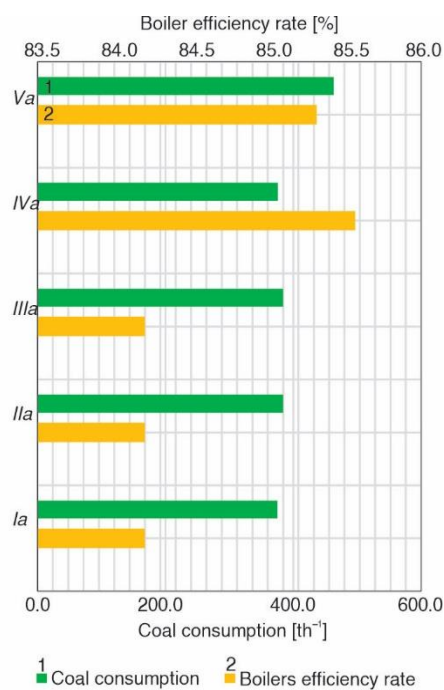


Figure 9. Change of boiler efficiency rate and total coal consumption for regimes *Ib-Vb*

Re-circulation of mill gaseous mixture decreases temperature of drying fluid at mills entrance thus providing possibility to reduce primary air-flow at same milling capacity rate and mill gaseous mixture temperature.

Also it is important to state that increase in re-circulation reduces mass-flow of mill gaseous mixture gas phase guided to the boilers burners thus reducing its velocity at burners outlet. This additional effect supports optimizing secondary air/mill gaseous mixture velocity ratio at lower mill gaseous mixture re-circulation rates.

Already at $r_{mg} = 0.3$ this velocity ratio is cca. 1.3. Ratio of cca. 2.0 (value within optimal range) can be obtained when number of mills in operation is reduced by 1.0. Fully optimized ratio (2.5) can be achieved with boiler steam production of 795 t per hours if air leakages in furnace and milling plant are reduced from 0.41 to 0.21 as shown in fig. 10. Value of 2.5 is kept when boilers steam production is increased to the nominal level (974 t per hours).

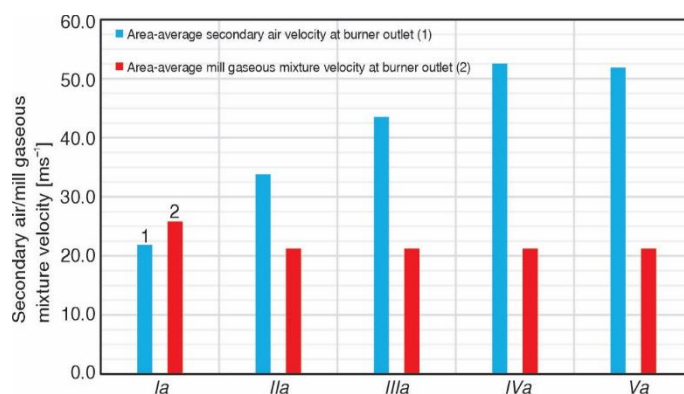


Figure 10. Change of secondary air and mill gaseous mixture velocity at burner outlet for regimes Ib-Vb

Although there are numerous benefits in applying re-circulation of mill gaseous mixture in this particular case, this modification will bring higher power consumption of mill as well intensified wearing of its operating elements due to the increased concentration of coal particles in mill impeller. Also, due to the reduced primary air-flow, line 2, tab. 6, higher flue gas temperatures at re-circulation head are to be expected which might result in higher fouling and deformation of the shape of re-circulation openings in furnace. This would give additional aerodynamic losses in milling plant and, potentially, reduce maximum milling capacity.

Conclusions

Increasing milling capacity of existing fan mills along with retaining all other mill operational parameters is challenging task. Narrower approach implies using existing formulas for designing fan mill in order to detect appropriate measure for increasing fan mill output. Simple analysis of these formulas will eventually lead to the solutions such as increasing rotational speed of fan mill or increasing fan mill impeller diameter.

During 2012th increasing rotational speed of mill impeller for the purpose of obtaining higher milling capacity is performed at TPP *Nikola Tesla* Unit A6. According to the tests of milling plants performances taken after retrofits milling capacity is increased as well as fineness of grinding of output coal dust. However, this measure provided higher values of fan mill ventilation which, as consequence, resulted in enormous enlargement of primary air-flow thus reducing secondary air-flow brought to the coal dust burners. Occurred change of secondary air/mill gaseous mixture velocity ratio below optimal range postponed combustion process in furnace such that burning of coal dust particles has been relocated from the burner zone to the furnace hopper and outlet section of the furnace. Flue gas temperature at furnace outlet has been significantly increased in comparison to the design value while feedwater mass-flow in desuperheaters is enlarged to the extent of almost 20% of steam production rate. Flame propagation throughout furnace height is altered which makes combustion process less resistant to the variations in characteristics of entering coal particles.

Table 6. Milling plant measurement and thermal and aerodynamic calculation results

No.	Measured parameter	Unit	Value				Nominal steam production	
			Steam production – 795 t/h					
			<i>Ib</i> $r_{mg} = 0.15$	<i>IIb</i> $r_{mg} = 0.3$	<i>IIIb</i> 4 mills in operation	<i>IVb</i> Reduced air leak		
1	2	3	4	5	6	7	8	
1.	Rotational speed	%/min	526	526	526	526	526	526
2.	Primary air-flow	Nm ³ /h	57233	16726	16618	17143	24202	
3.	Air-flow per milling pant	Nm ³ /h	134573	134573	168211	206585	201657	
4.	Milling capacity	t/h	98.212	98.212	98.212	98.212	98.212	
6.	Water content in coal dust	%	18.76	18.76	18.76	18.76	18.76	
7.	Mill ventilation	Nm ³ /h	251830	251830	251830	251830	251830	
8.	Residue on sieve R1000	%	9.68	9.68	9.68	9.68	9.68	
9.	Residue on sieve R90	%	69.85	69.85	69.85	69.85	69.85	
10.	Mill gaseous mixture temperature	°C	186	186	186	186	186	
12.	Raw coal water content	%	50.7	50.7	50.7	50.7	50.7	
13.	Raw coal mineral matter content	%	13.3	13.3	13.3	13.3	13.3	
14.	Raw coal lower heating value	kJ/kg	8014.0	8014.0	8014.0	8014.0	8014.0	
15.	Area-averaged secondary air velocity at burner outlet	m/s	21.85	33.82	43.53	52.58	51.87	
16.	Area-averaged mill gaseous mixture velocity at burner outlet	m/s	25.83	21.27	21.27	21.27	21.27	
17.	Mill gaseous mixture re-circulation flow	Nm ³ /h	37760.0	75524.0	75524.0	75524.0	75524.0	

In order to reduce occurred negative effects in this paper two measures are proposed. Partial substitution of high amount of primary air for cooling milling plant might be performed by re-circulation of cold flue gases at boiler outlet. However, thermal and aerodynamic calculations showed that higher re-circulation rates (>0.2) are required to achieve better secondary air/mill gaseous mixture velocity ratio. Optimal values of this ratio are still unattainable due to the higher values of mill gaseous mixture velocity at burners outlet provoked by increased fan mill ventilation at higher impeller rotational speed. When re-circulation rate is at level of 0.2, this ratio is 1.5 which is still below minimal value of its optimal range (2.0-3.0). Also, calculations showed that application of this measure also implies reducing boiler efficiency rate and increase of coal consumption for the same boilers heat output.

Second proposed, less conventional, measure in this paper is re-circulation of mill gaseous mixture from the mill gaseous mixture duct to the mill intake. As previous measure, re-circulation of mill gaseous mixture would reduce need for dosing of primary air into milling plant for the purpose of maintain mill gaseous mixture temperature which would ensure more favorable furnace operation with increased mill impeller rotational speed. Additionally, this re-circulation would provide reducing mill gaseous mixture velocity at furnace inlet and thus support bringing closer velocity ratio to the optimal range. At re-circulation rate of 0.3 and boiler work with 1 mill less in operation this ratio is at level of cca. 2.0, that is, at lower boundary of optimal range. Reducing air leakages to the milling plant and furnace will further increase its value and provide fully optimized operation of furnace not losing previously achieved increase

in milling capacity. It is to be pointed out that re-circulation of mill gaseous mixture at milling plant will increase concentration of solid phase within mill and thus increase mill consumption and its wearing intensity. Also, additional monitoring should be taken on temperature of drying fluid in re-circulation head of milling plant since this re-circulation will result in its increase and potentially increased fouling of the area in the vicinity of hot gas re-circulation openings.

Acknowledgment

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