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

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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.

Keywords*: Milling plant, lignite combustion, coal milling, aerodynamic calculation.*

1. Introduction

For the purpose of maintaining stable and optimal combustion process within boilers furnace low caloric 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.

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 recirculated 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):

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

where:

B_{max}	-	[kg/s]	-	maximum milling capacity;
k_1	-	[-]	-	coefficient that depends on type of coal and type of milling process;
k_2	-	[-]	-	mill impeller wear coefficient;
n	-	[s^{-1}]	-	rotational speed;
D_1	-	[m]	-	mill impeller outer diameter;
b	-	[m]	-	width of mill impact plates;
k_H	-	[-]	-	coal Hardgrove grindability coefficient;
k_3	-	[-]	-	coefficient of coal dust water content;
k_4	-	[-]	-	coefficient of coal water content;

R_{5000}	-	[%]	-	coal residue on sieve of 5.0 mm;
R_{90}	-	[%]	-	coal dust residue on sieve of 0.09 mm.
m	-	[-]	-	coal sort exponent.

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

$$\dot{m}_{B\,tr} = C \cdot M_{Ha} \cdot \left(\ln \frac{100}{R_{90}}\right)^{-0.5} \cdot D_a \cdot B_i \tag{2}$$

where:

$\dot{m}_{B\,tr}$	-	[t/h]	-	maximum milling capacity;
C	-	[-]	-	coefficient that depends outlet tangential speed of mill impeller;
M_{Ha}	-	[-]	-	coal Hardgrove grindability coefficient;
D_a	-	[m]	-	mill impeller outer diameter;
B_i	-	[m]	-	width of mill impact plates;
R_{90}	-	[%]	-	coal dust residue on sieve of 0.09 mm.

Additional submodels of second formula in which influence of coal maceral composition on overall milling capacity is elaborated can be found in PhD dissertation [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 equations (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 equations (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 equations (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.

2. 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 temp.	t_{ST}	=	543	^oC
Nominal reheated steam production	$\dot{m}_{RH}$	=	228.78	kg/s
Reheated steam pressure	p_{RH}	=	4.2	MPa
Reheated steam temp.	t_{RH}	=	543	^oC
Reheated steam pressure at boilers inlet	p_{CRH}	=	4.5	MPa
Reheated steam temp. at boilers inlet	t_{CRH}	=	333	^oC
Feedwater pressure	p_{FW}	=	21.3	MPa
Feedwater temperature	t_{FW}	=	248	^oC

Table 2. Fan mill design parameters.

Mill designation	EVT - N 270.45
Maximum milling capacity	25.83 kg/s (93 t/h)
Nominal milling capacity (guaranteed coal)	23.61 kg/s (85 t/h)
Rated ventilation for nominal milling capacity	205,000 Nm^3/h
Rotational speed of mil impeller	420 ÷ 480 (490) ^{o}/min
Mill gaseous mixture temperature	180 ^oC
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 figure 1 on the left. When mill is in operation hot recirculated gases at furnace outlet are brought to the recirculation 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.

During second half of first decade of 20^{th} 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.

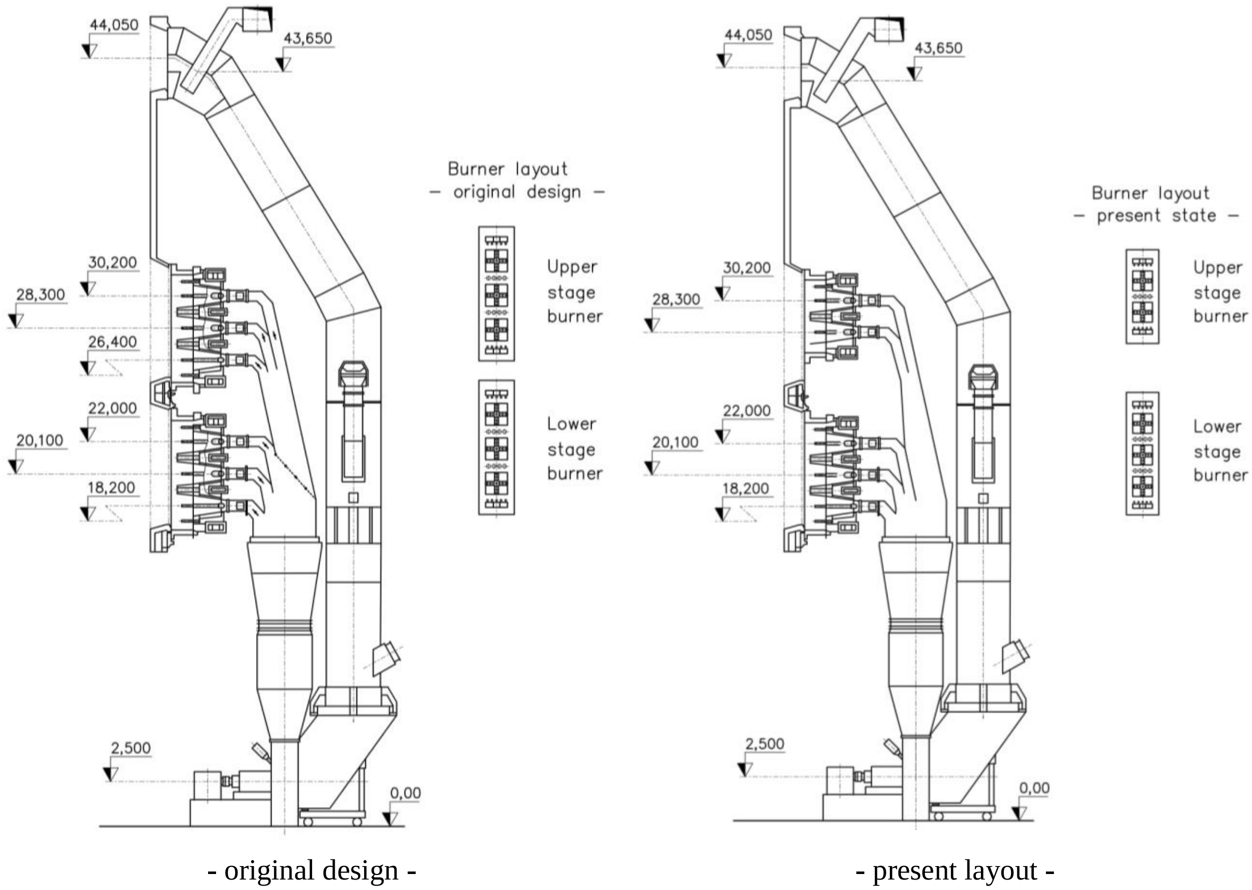

Figure 1. Coal preparation plant at TPP "Nikola Tesla" A6 with burners layout before (left figure) and after modification (right figure).

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 ^{o}/min, and, afterwards, even to the 530 ^{o}/min. This value is kept up to now and adopted as new nominal value.

3. 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.

When comparing data from tab. 3 and design mill parameters form 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 h), 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.

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	-	-	97,770.0	97,743.0
3.	Air flow per milling plant	Nm^3/h	107,000.0	126,000.0	131,800.0	131,879.0
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	**267,620.0**	**248,119.0**	**251,744.0**	**251,823.0**
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	7,186.0	5,894.0	8,014.0	8,014.0
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

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 then 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 form (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-NOx 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
1	*2*	*3*	*4*	*5*
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	ºC	534/533	533
7.	Reheated steam pressure	bar	30/30	30
8.	Reheated steam temperature	ºC	538/537	538
9.	Reheated inlet steam temperature	ºC	325	325
10.	Feedwater pressure	bar	171	171
11.	Feedwater temperature	ºC	178	178
12.	Injection in desuperheaters	t/h	150	150
14.	Hot air flow	Nm^3/h	656,000.0	672,857.0
15.	Air temperature at air-preheater inlet	ºC	40/40	40
16.	Air temperature at air-preheater outlet	ºC	249/249	251
17.	Flue gas temperature at air-preheater inlet	ºC	265/264	265
18.	Flue gas temperature at air-preheater outlet	ºC	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	ºC	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).

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/h) to the superheated steam production (795 t/h)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. CFD calculations are performed entirely according to the model given in [16]. In fig. 2atemperature field in longitudinal furnace cross section is shown while isotemperature contours for the same calculation domain are given in fig. 2b. 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. 2a 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 then 1400 K are located below burners zone and in the vicinity of furnace outlet as it is shown on fig. 2a. Contrary to that, when combustion process is optimized flue gas high temperature zones are formed in burner zone (fig. 3a). 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. 3b.

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.

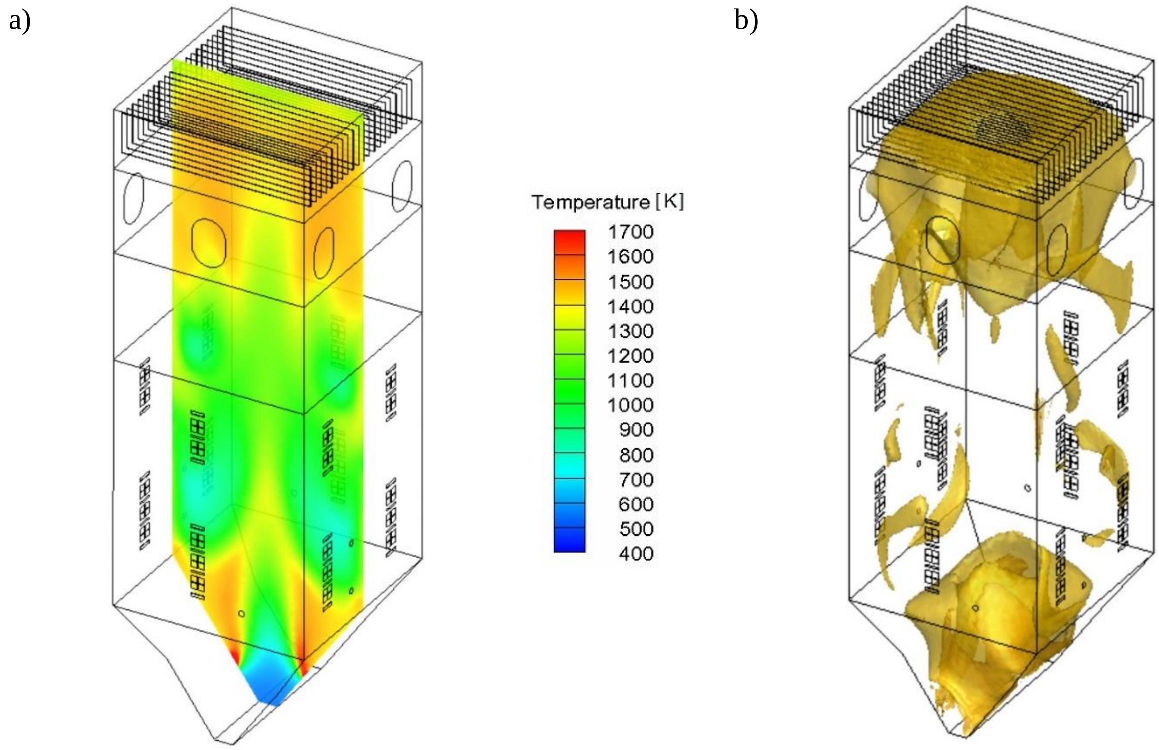

Figure 2. Temperature field in furnace for power steam boiler at TPP „Nikola Tesla A" Unit 6 at present state (non-optimized secondary air/mill gaseous mixture velocity ratio).

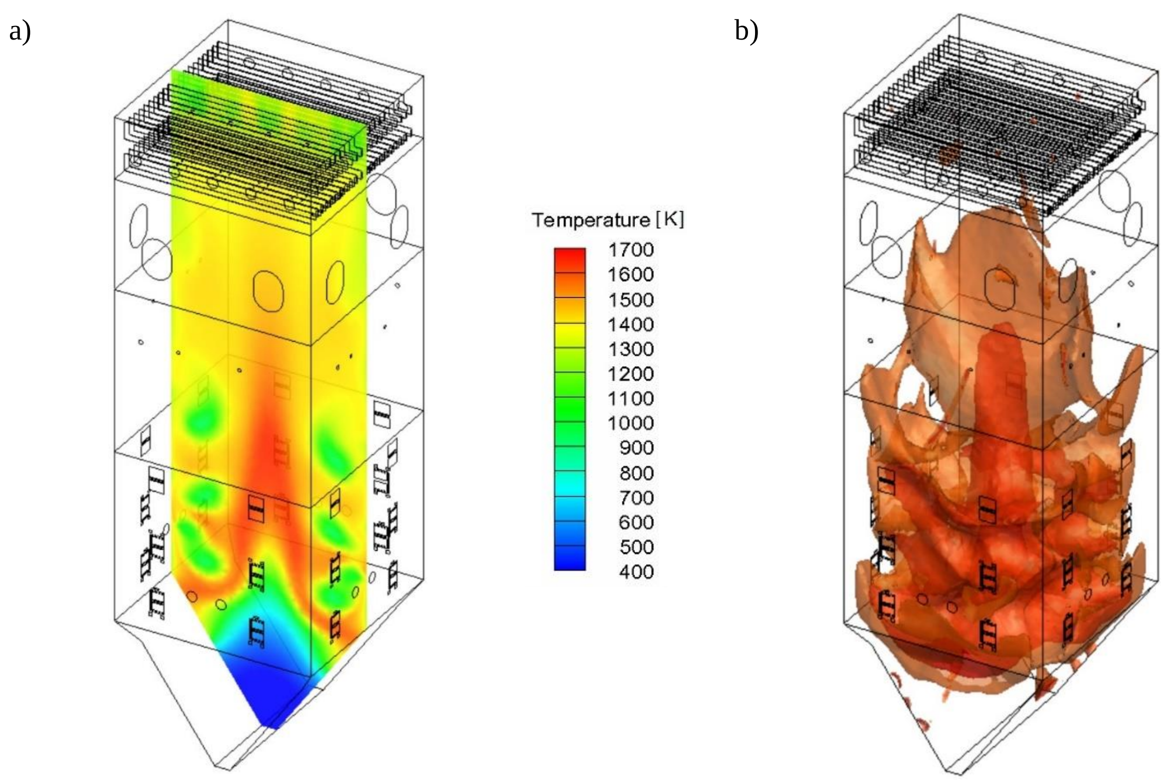

Figure 3. Temperature field in furnace for power steam boiler of 350 MWel nominal unit output and optimized secondary air/mill gaseous mixture velocity ratio.

4. 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.

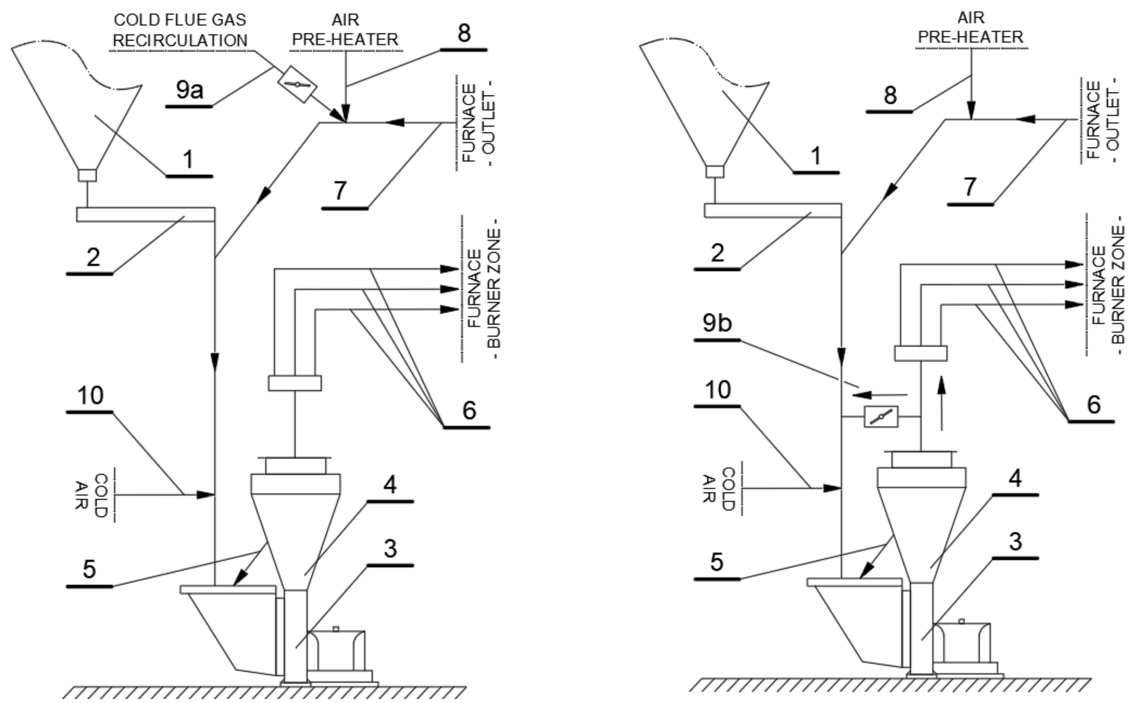

Figure 4. Milling plant scheme with: a) recirculation of cold flue gases; b) local recirculation of mill gaseous mixture.

1) Coal bunker; 2) Coal feeder; 3) Fan mill; 4) Mill inertial separator; 5) Separators recirculation; 6) Coal dust burners levels; 7) Recirculation of hot gases at furnace outlet; 8) Primary air line; 9a) Recirculation of mill gaseous mixture; 9b) Recirculation of cold flue gases; 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. 4a. 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 recirculation of mill gaseous mixture locally, in every milling plant separately, according to the scheme given in fig. 4b. 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 recirculation 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.

4.1. Recirculation of cold gases at boilers outlet

Effects of recirculation of cold flue gases are analyzed in cases when recirculation rate (acc. to definition given in [1]) is set at values of 0.1, and 0.2 (regimes *Ia* and *IIa* in tab. 5). Higher values of recirculation 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*).

When cold gas recirculation 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.

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 recirculation rate certainly reduces overall hot air flow as well as secondary airflow per milling plant it decreases need for dosing of primary air in recirculation head providing somewhat increase in secondary air velocity at burners outlet. However, this increase is

Table 5. Recirculation of cold flue gases – power boiler thermal calculation results.

No.	Parameter	Unit	Value				
			Steam production rate – 795 t/h				*Va* Nominal steam production
			Ia $r_2 = 0.1$	*IIa* $r_2 = 0.2$	*IIIa* 4 mills in operation	*IVa* Reduced air leak.	
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
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	ºC	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	ºC	538	538	538	538	543
9.	Reheated inlet steam temp.	ºC	325	325	325	325	333
10.	Feedwater pressure	bar	171	171	171	171	213
11.	Feedwater temperature	ºC	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	636,820	598,738	598,675	759,043	941,901
15.	Air temperature at air-preheater inlet	ºC	40	40	40	40	40
16.	Air temperature at air-preheater outlet	ºC	271	288	288	279	295
17.	Flue gas temperature at air-preheater inlet	ºC	280	294	294	292	311
18.	Flue gas temperature at air-preheater outlet	ºC	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	ºC	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

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 recirculation rates (for ex. 0.3). One direction to consider is to reduce mill ventilation not altering its maximum capacity, if possible.

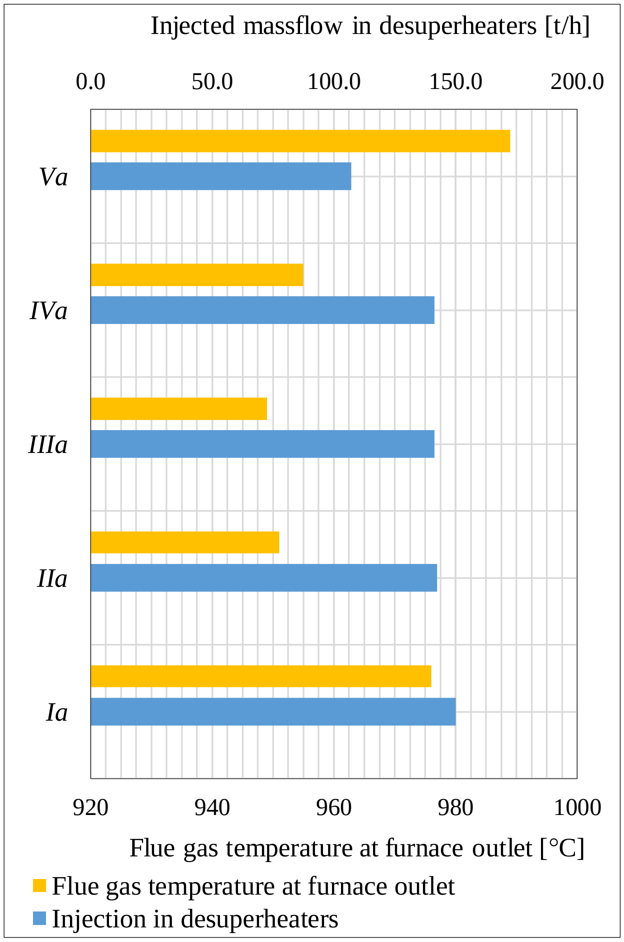

Figure 5. Change of feedwater mass flow in desuperheaters and flue gas furnace outlet temperature for regimes *Ia – Va*.

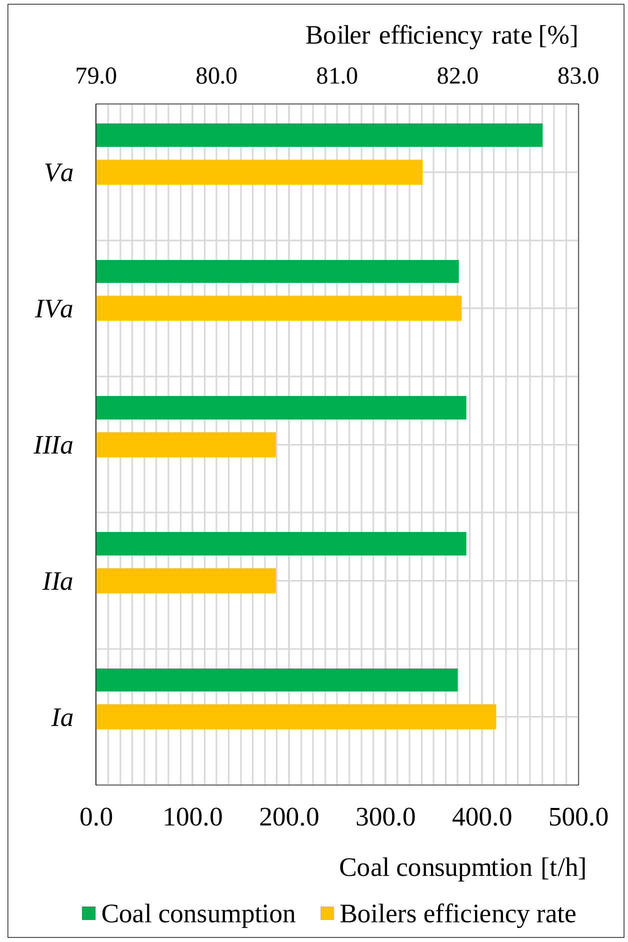

Figure 6. Change of efficiency rate and coal consumption of boiler for regimes *Ia – Va*.

Table 5. Recirculation 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
2.	Primary air flow	Nm^3/h	70,898	45,061	44,827	43,214	50,501
3.	Air flow per milling pant	Nm^3/h	127,364	119,748	149,668	189,761	188,380
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	251,830	251,830	251,830	251,830	251,830
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

Extension of table 5

9.	Mill gaseous mixture temperature	ºC	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	8,014.0	8,014.0	8,014.0	8,014.0	8,014.0
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

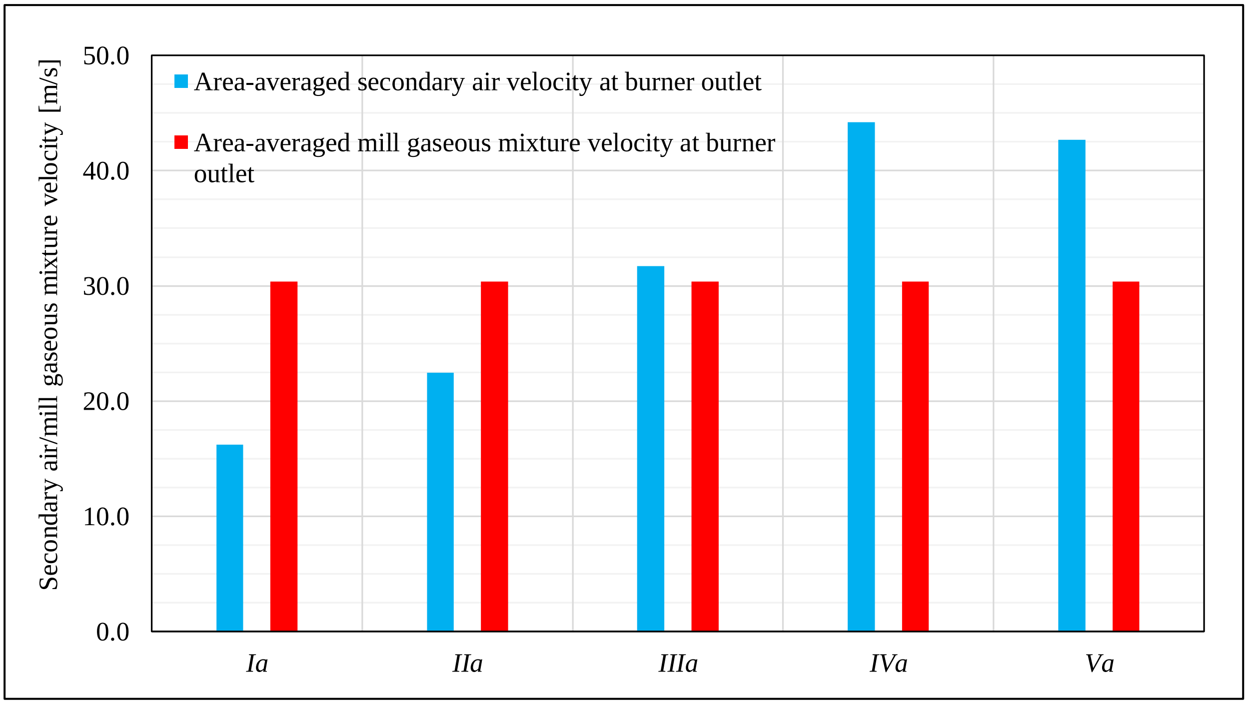

Figure 7. Change of secondary air and mill gaseous mixture velocity at burner outlet for regimes *Ia* – *Va*.

4.2. Recirculation of mill gaseous mixture within milling plant

Recirculation of mill gaseous mixture in milling plant is analyzed for recirculation rates of 0.15 and 0.3 (regimes *Ib* and *IIb*). 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 al measures applied are also provided (regime *Vb*).

This measure, unlike recirculation 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.

Recirculation of mill gaseous mixture decreases temperature of drying fluid at mills entrance thus providing possibility to reduce primary airflow at same milling capacity rate and mill gaseous mixture temperature.

Also it is important to state that increase in recirculation 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 recirculation 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/h 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/h).

Although there are numerous benefits in applying recirculation 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 higher flue gas temperatures at recirculation head are to be expected which might result in higher fouling and deformation of the shape of recirculation openings in furnace. This would give additional aerodynamic losses in milling plant and, potentially, reduce maximum milling capacity.

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

No.	Measured parameter	Unit	Value				
			Steam production – 795 t/h				*Vb* Nominal steam production
			Ib r_{mg} = 0.15	*IIb* r_{mg} = 0.3	*IIIb* 4 mills in operation	*IVb* Reduced air leak.	
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1.	Rotational speed	°/min	526	526	526	526	526
2.	Primary air flow	Nm^3/h	57,233	16,726	16,618	17,143	24,202
3.	Air flow per milling pant	Nm^3/h	134,573	134,573	168,211	206,585	201,657
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	**251,830**	**251,830**	**251,830**	**251,830**	**251,830**
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	ºC	186	186	186	186	186
12.	Raw coal water content	%	50.7	50.7	50.7	50.7	50.7

Extension of table 6

13.	Raw coal mineral matter content	%	13.3	13.3	13.3	13.3	13.3
14.	Raw coal lower heating value	kJ/kg	8,014.0	8,014.0	8,014.0	8,014.0	8,014.0
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 recirculation flow	Nm^3/h	37,760.0	75,524.0	75,524.0	75,524.0	75,524.0

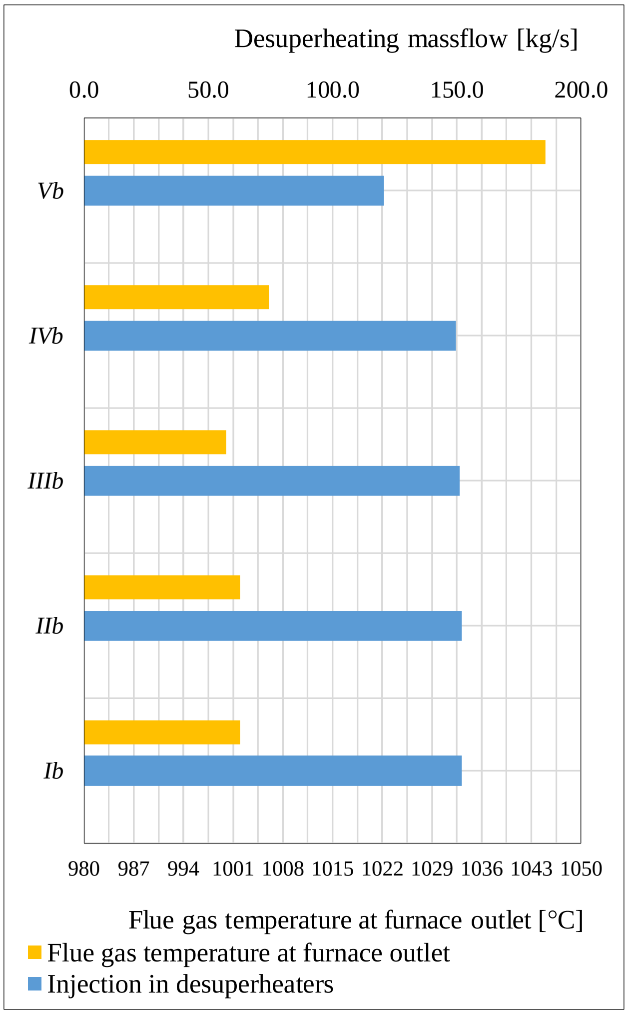

Figure 8. Change of desuperheating mass flow and flue gas temperature at furnace outlet for regimes *Ib – Vb.*

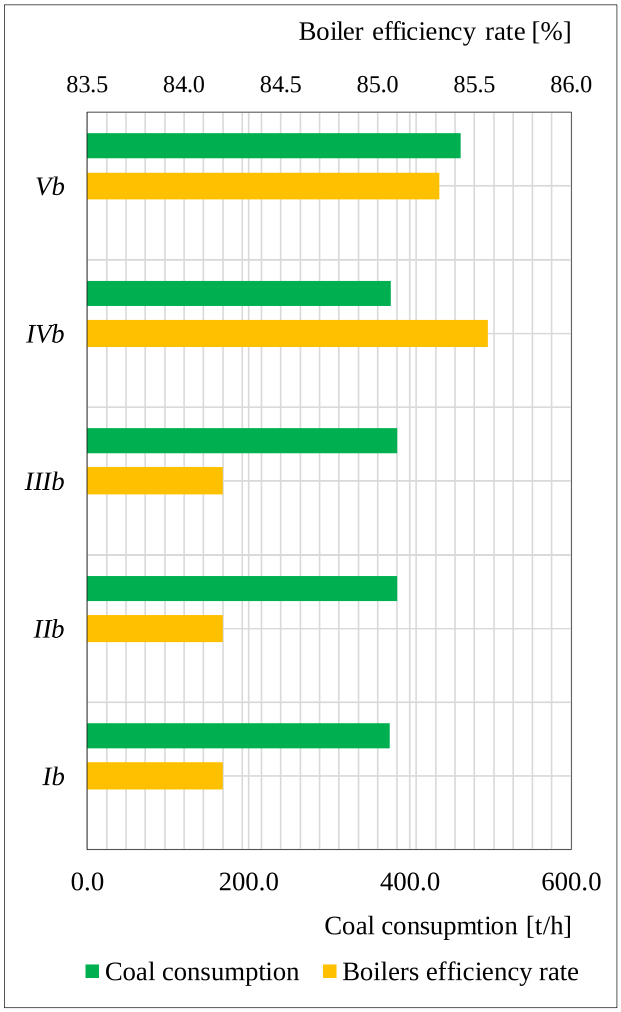

Figure 9. Change of boiler efficiency rate and total coal consumption for regimes *Ib – Vb.*

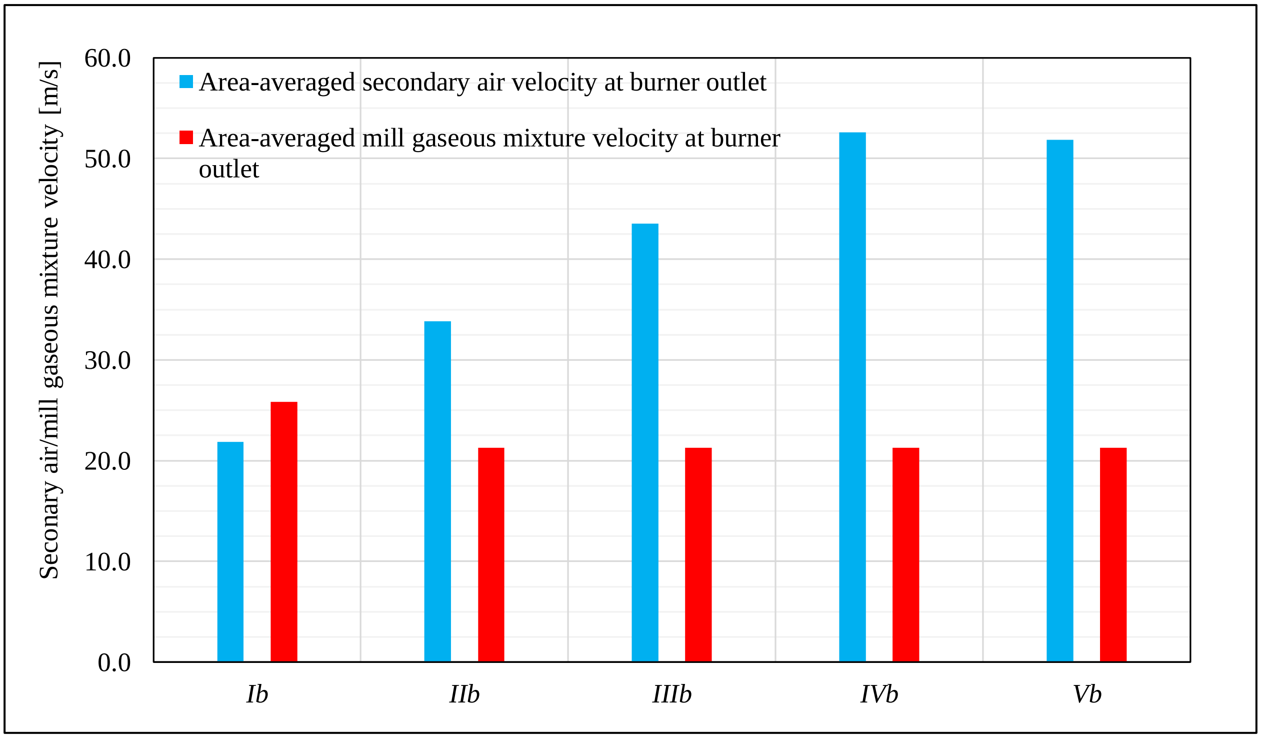

Figure 10. Change of secondary air and mill gaseous mixture velocity at burner outlet for regimes *Ib* – *Vb*.

5. Conclusion

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.

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 recirculation of cold flue gases at boiler outlet. However, thermal and aerodynamic calculations showed that higher recirculation 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 recirculation 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 recirculation of mill gaseous mixture from the mill gaseous mixture duct to the mill intake. As previous measure, recirculation 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 recirculation would provide reducing mill gaseous mixture velocity at furnace inlet and thus support bringing closer velocity ratio to the optimal range. At recirculation 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 loosing previously achieved increase in milling capacity. It is to be pointed out that recirculation 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 recirculation head of milling plant since this recirculation will results in its increase and potentially increased fouling of the area in the vicinity of hot gas recirculation openings.

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