Analysis of slagging phenomena at Reftinskaya Power Plant

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Abstract

Reftinskaya power plant, belonging to ENEL Russia electric utility, is one of the largest power stations in the Russian Federation. Located 120 km north-east of Ekaterinburg, Reftinskaya Power Station (RGRES) is composed of six 300 MWe units and four 500 MWe units, supplied predominantly with coal extracted from Ekibastuz basin, in Kazakhstan.
The 300 MWe units, fed exclusively with coal from Ekibastuz basin, suffer of problems related to slag formation and deposition in the cold hoppers of the furnace. In some cases the increase of slag deposit volume leads to the clogging of the hopper discharge section which, in turn, forces to shutdown the boiler for the slag removal. This issue determines significant loss of profits due to both the hopper cleaning operation cost and the loss of generated electricity during the unit stop.
In this context, the ENEL Global Generation R&D department (ENEL Research) is performing an activity aimed at assessing the root causes of the slag formation in the six 300 MWe units of RGRES, and is proposing improvement solutions capable of increasing the units availability. The problem analysis has been developed by collecting operational data in dedicated experimental campaigns, by laboratory analyses to determine the coal and ash characteristics and by evaluating possible improvements with the aid of numerical thermo-fluidodynamic modelling tools (1-D and 3-D).
The preliminary results show promising possibilities to reduce the slag formation through a strict control of the combustion process. In addition, techniques to monitor the evolution of the slagging deposition phenomenon are under evaluation.

Reftinskaya Power Plant

Reftinskaya Power Plant is one of the largest generation plants in the Russian Federation. It is composed of four 500 MW units and six 300 MW units.

The six 300 MW units at ENEL Russia Reftinskaya Power Station suffer from the initial plant start-up of a problem of slag formation and deposition in the cold hopper of the furnace. These events frequently lead to the shutdown of the boiler for slag removal, causing a significant cost for both the direct cost related to cleaning, and to the loss of generated electricity during the unit stop.

The 300 MW units have a single turbine fed by two identical steam generators PK-39 II, each supplying 450 t/h of superheated steam at 230 bar and 545 °C. Boilers supply also reheated steam at 32 bar / 545 °C. A boiler is equipped with 4 hammer mills, each feeding coal to an horizontal row of 3 burners. Full load can be achieved with one mill out of service in one of the two boilers, therefore with a total of 7 mills in service. The 12 burners in one boiler are arranged in two levels, on the front and rear wall (opposed-fired arrangement). A boiler schematic is reported in Figure 1.

The boilers are exclusively fed with coals from the Ekibastuz basin, from Kazakhstan. A typical analysis of the Ekibastuz coal is reported in Table 1.

COAL ORIGIN		**EKIBASTUZ**
Supplier		**BOGATYR**
Ultimate analysis, as received		
Carbon	%	45,72
Hydrogen	%	2,66
Nitrogen	%	0,86
Sulfur	%	0,52
Oxygen (by diff.)	%	6,14
LHV	MJ/kg	17,12
LHV	kcal/kg	4089
Proximate analysis, as received		
Moisture	%	5,00
Ash	%	39,10
Volatile Matter	%	18,19
Fixed Carbon (by diff.)	%	37,71
Fuel Ratio FC/VM	-	2,07
HGI Index	-	n.d.
Major elements in ash		
Al_2O_3	%	26,4
CaO	%	2,4
Fe_2O_3	%	4,3
K_2O	%	0,5
MgO	%	0,8
MnO_2	%	0,1
Na_2O	%	0,4
P_2O_5	%	0,4
SiO_2	%	58,8
TiO_2	%	1,3

Table 1 – Typical analysis of Ekibastuz coal

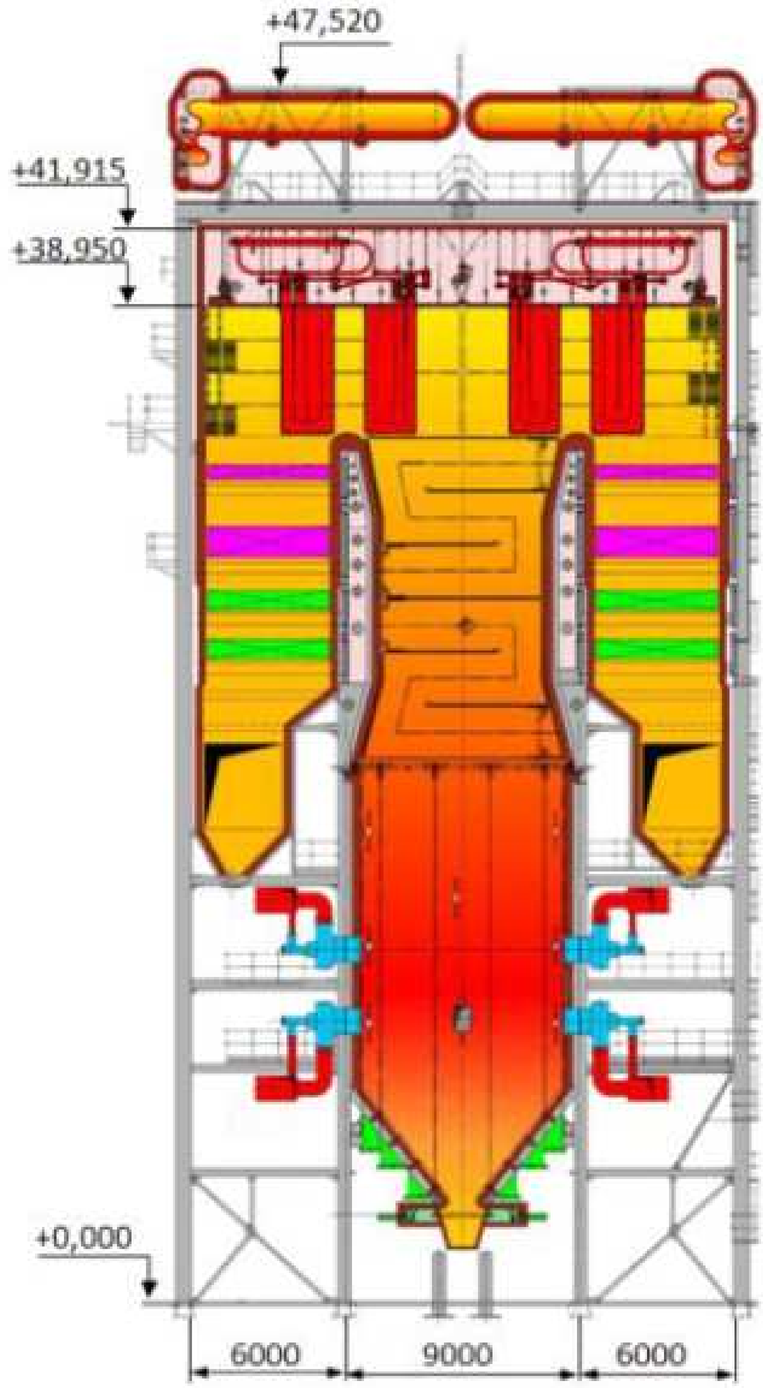


Figure 1 – Reftinskaya PK-39 II boiler schematic

The slagging problem

Since plant start-up in 1975 the six 300 MW units have been subjected to a problem of slag accumulation in the furnace hopper. In the most severe cases the accumulation takes place very rapidly, leading in a short time to the obstruction of the hopper discharge section and forcing to boiler shutdown to remove the slag. An example of the slag accumulation is shown in Figure 2.

Figure 2 – Furnace hopper plugged by slag accumulation

The overall statistics about the phenomenon reports that this event takes place on average about 1÷2 times a year for each boiler, but sometimes the frequency is higher. In addition, there are events when the accumulation of slag is not very fast, and the plant staff can intervene to clean the boiler, thus avoiding the shutdown.

The mechanical design of the hopper has a strong influence, due to the narrow space of the discharge section, further on reduced by the inclination of the side walls toward the hopper centre. Another negative aspect is the horizontal layout of the steam tubes. In fact when the refractory bricks below the tubes are disrupted the tubes become misaligned, creating an obstacle to the regular ash discharge. This circumstance is confirmed by the fact that, after a complete replacement of the hopper tubes, the frequency of shutdown events is reduced, and progressively increases with the tube wear, see Figure 3.

To identify other possible root causes of the phenomenon, a study is being conducted by ENEL Research, with a comprehensive analysis developed in the following research lines:

- laboratory analyses to determine the coal and ash characteristics;
- on-field tests to collect boiler operation data;
- numerical modelling of both the boiler thermo-fluidodynamics (one-dimensional and three-dimensional models) and the ash thermodynamic behaviour.

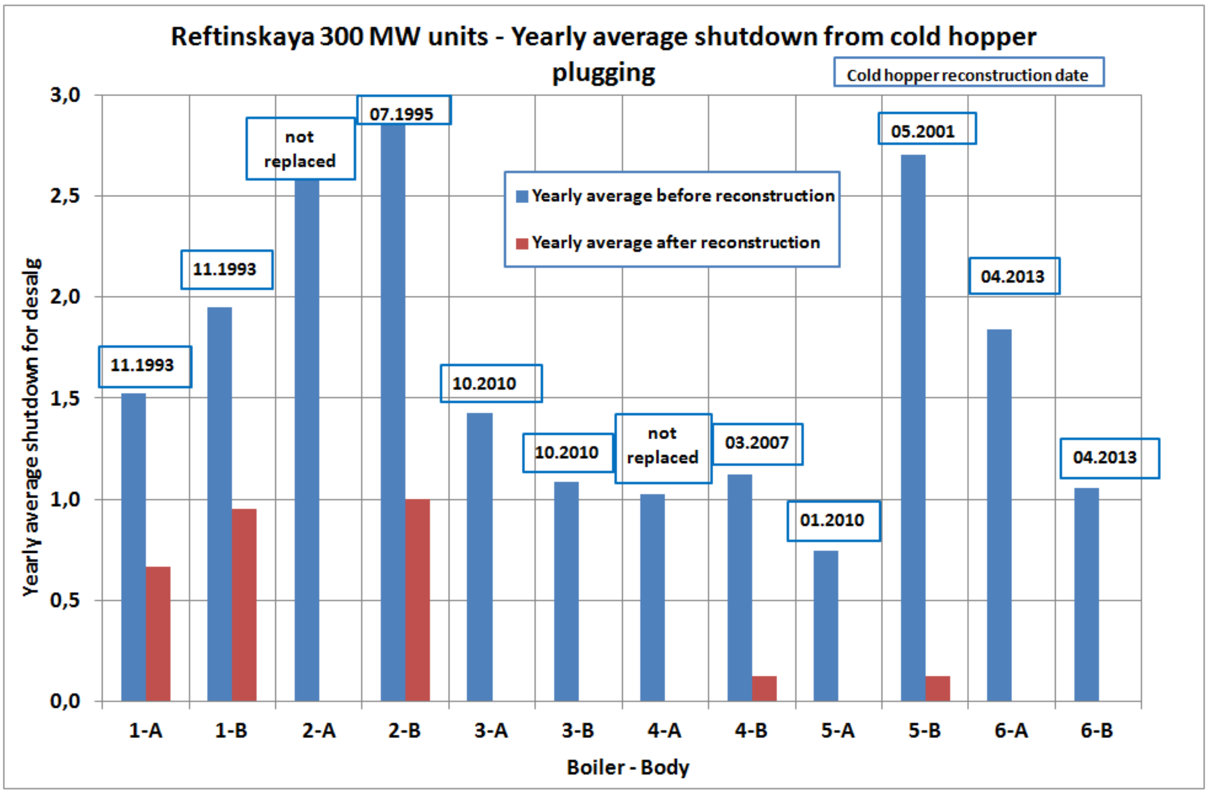


Figure 3 – Statistics of slagging events causing unit shutdown

Experimental campaigns

Several testing campaigns have been carried out in some PK-39 II boilers, with the aim of collecting data to set up the boiler models and to analyze deeply the boiler operating conditions.

All the operating parameters that in principle can influence the ash deposition pattern have been investigated, in particular:

- the coal flow distribution to the burners fed by one mill;
- the coal particle size distribution at mill exit;
- the primary/secondary air distribution to the burners;
- the burner swirler setting.

As the boiler can be operated with one mill out of service, the influence of the parameters indicated above has been considered in the 4-mills and 3-mills configuration, and particularly with one mill at the upper level out of service, which is the worse condition with respect to the ash accumulation in the hopper.

Measurements of coal flow distributions have been conducted in selected mills by using a rotating probe, according to ISO 9931, showing a very limited spread in the coal flows to the 3 burners fed by one mill, see Figure 4.

The coal particle size distribution measured on the collected samples resulted to be well within the specifications, although the fineness is reduced when operating with 3 mills, as shown in the Rosin-Rammler chart in Figure 5.

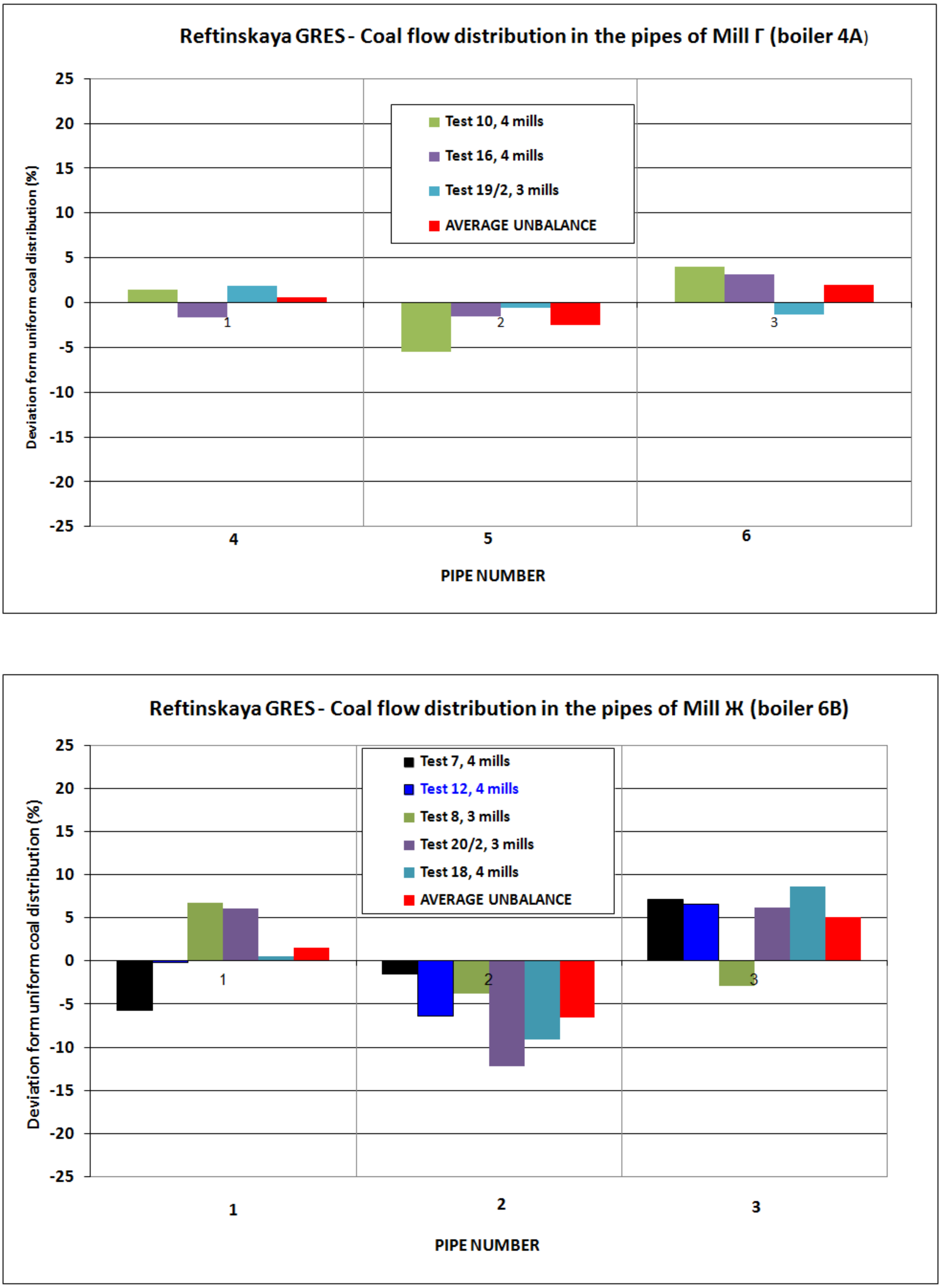


Figure 4 – Examples of measured coal flow distributions among the coal pipes

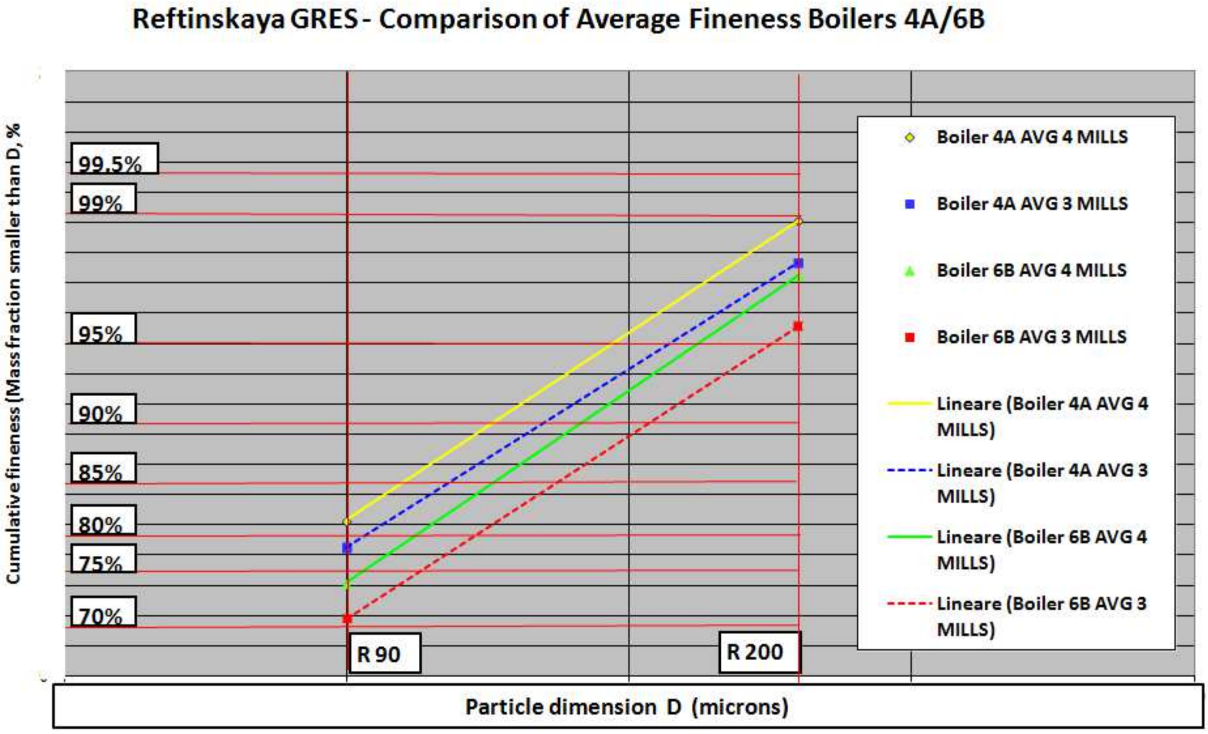
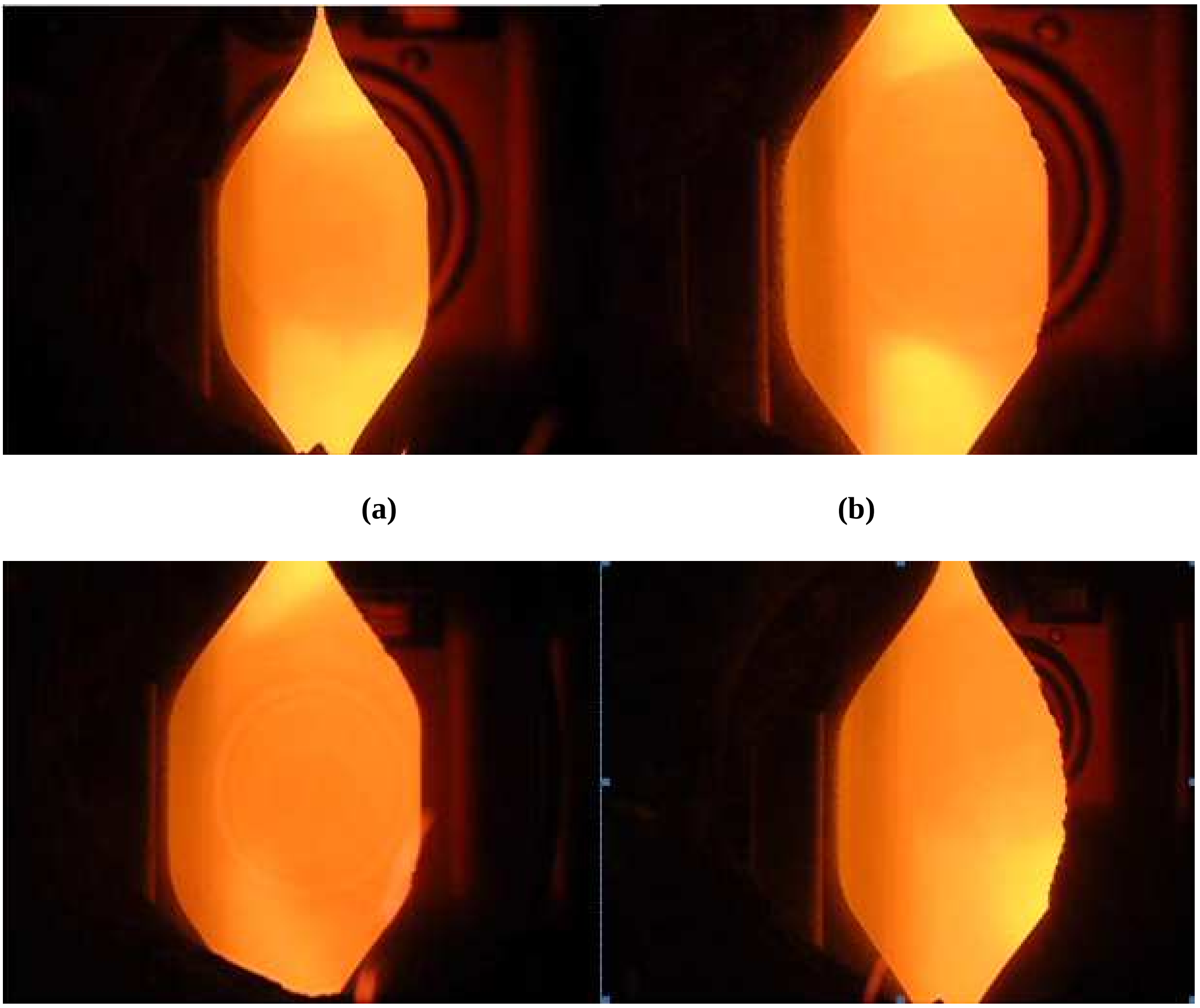


Figure 5 - Rosin Rammler chart, comparison of boiler 4A/6B mills

To evaluate the distribution of secondary air flow to the burners, as the boilers are not equipped with instruments connected to the Supervision System, pressure tapping points have been realised at the burner inlet, before the swirler blades. The measurements have shown systematically higher values at the upper level, although very low as absolute values (about 25 mm w.g. at the lower elevation, compared with an average of 40 mm w.g. at the upper level). This difference, found in boiler 4A (one of the most affected in recent times by the slagging problem), indicates a higher secondary air flow at the upper burner level. The measurement has been repeated in boiler 6, finding a lower difference. In this boiler, grid velocity measurements have been also carried out in the secondary air duct to each burner, showing a very small flow difference.

An important difference of units 1-2-3-4 versus 5 and 6 is the measuring chain of the coal flow. In units 1-2-3-4 the measuring device is incorporated in the feeder shaft, and the signal is subject to a significant drift (up to 50%, as checked during the tests), while the more recent units have a very stable signal of the coal flow. The drift of the signal can cause a big error in the estimation of the true coal mill flow, possibly causing an excessive feeding of coal to the lower level burners, in particular when one upper mill is out of service.

The burner swirler setting can also influence the amount of ash falling into the hopper, as described in detail in the section about boiler modelling. For this reason tests have been also conducted changing the burner swirler, which is controlled by a series of radial blades. The design swirler position (“zero”) corresponds to a blade position of 45°. The jets closer to the “axial” direction, corresponding to a lower blade opening angle, are expected to reduce the amount of ash approaching the cold hopper. By changing the swirler position, the flame pattern changes accordingly, as shown in Figure 6.



(a) (b)

(c) (d)

Figure 6 – Photos of burner No 1 at different swirler angles

(a) :-10° (b) : 0° (c) : +10° (d) : +20°

Boiler modelling

Boiler modelling has been carried out with the aim of investigating the thermo-fluidodynamic field and assessing the effect of some operational parameters on slagging formation. Moreover, it has been used to support the experimental activities, particularly for the selection of the boiler configurations to be characterised during the on-field tests.

Computational fluid-dynamic (CFD) modelling has been performed with the commercial code Ansys-Fluent release 15 code run on 32 core parallel cluster, installed in the computing facility located in the Enel Research headquarter in Pisa. The Fluent code represents the state-of-the art of commercial CFD codes for the combustion process modelling. In the specific case discussed in this paper, a steady-state solver has been used with a RANS (Reynolds

Average Navier-Stokes) equations approach for the turbulence modelling; in particular, two-equation k-ε Realizable turbulence model has been used.

A three dimensional geometric model of the RGRES 300 MW boiler was built with the Ansys Design Modeler software, replicating with high accuracy the geometric details of both the boiler and the burners. Then, the computational grid has been built with the Ansys Meshing software by employing 8 million cells (both hexahedral and tetrahedral types). Figure 7 shows a picture of the computational grid.

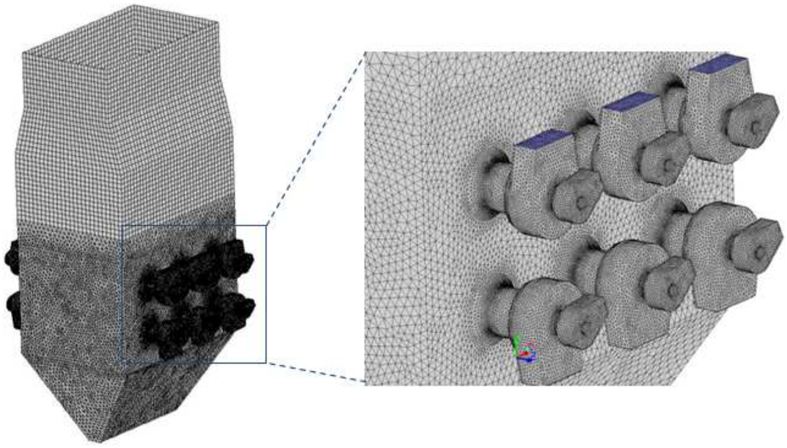


Figure 7 – Boiler computational grid realised for the CFD modeling

CFD modelling has taken into consideration the nominal load configuration with three and four mills in operations. In particular, the effect of several operational parameters on the slagging formation has been analysed by simulating variations with respect to their nominal settings. The considered operational parameters and the analysed variations are listed below:

- Angle of the burner swirler blade: -10° ÷ + 20° (deviation respect to 45° nominal setting, corresponding to zero)
- Coal flow rate bias on upper burner levels: 0 ÷ 15% (deviation from the nominal setting featured by homogeneous distribution between lower and upper burners).

The boiler data used to set up the CFD model boundary conditions have been extracted from the one-dimensional heat transfer model realised with the PROATES™ code, able to reconcile plant data (taken from the plant supervision system) and to calculate the heat transfer to the main boiler sections.

Figure 8 reports the map of the gas temperature fields at nominal load with three (left) and four (right) mills in service. Afterwards, the effect of the swirler on the flame shape has been assessed by modelling a new configuration featured by a reduced swirler blade angle (35°) in the four mill configuration, see the gas temperature maps on a horizontal plane in Figure 9. The pictures show that the flame shape corresponding to the nominal setting of the burner swirler is quite wide: in fact, the air jets (blue colour) do not penetrate inside the combustion chamber but adhere to the boiler walls.

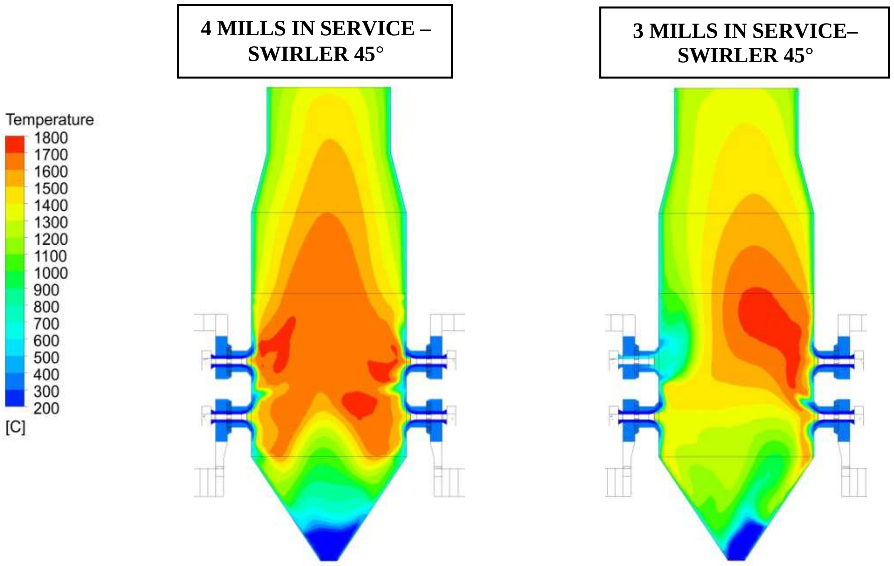


Figure 8 – Gas temperature maps on a vertical plane crossing the burners with four (left) and three (right) mill in operation

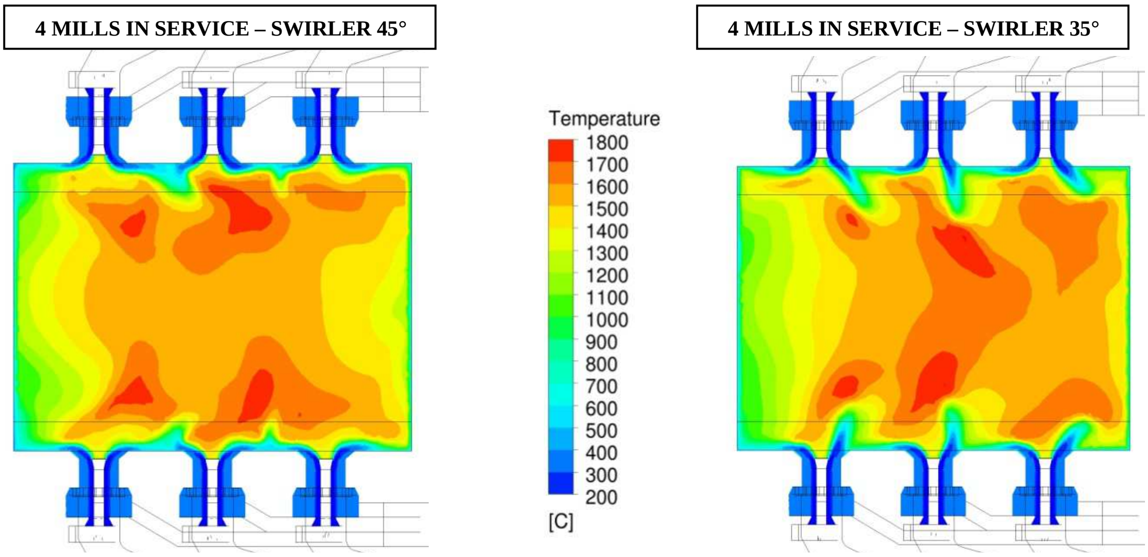


Figure 9 – Gas temperature maps on a horizontal plane (upper burners) for different swirler settings (nominal 45° in the left, modified 35° on the right)

Temperature maps in Figure 9 show that the swirler angle reduction leads to a narrower flame shape, featured by the complete penetration of the combustion air jet into the furnace and, consequently, better air-coal mixing. The effect of the swirler blade angle on the coal particle flow to the cold hopper was assessed by calculating the impact rate of coal particles on the surfaces of the bottom hopper[1]. It has to be noticed that the particle impact rate expresses only a qualitative (but not quantitative) relation with the slagging formation probability (i.e., keeping constant the other parameters, the higher the impact rate, the higher the slagging accumulation once the deposit starts to grow).

Taking as reference setting the 45° blade angle, the variation of the impact rate was calculated for the 25° and 35° blade angle positions (Figure 10Figure). Plot of Figure 10 shows that a reduction of the particle impact rate on the bottom hopper of about 11% can be obtained by reducing the blade swirler setting of about 10°, changing the blade angle from 45° to 35°. A reduction of the angle to 25° does not lead to a significant further reduction of the particle impact rate.

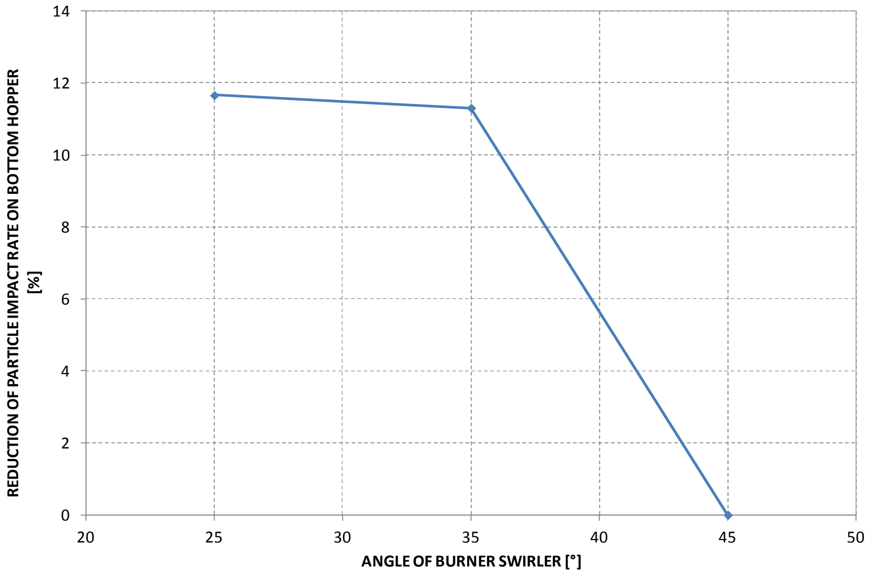


Figure 10 – Effect of the burner swirler setting on the particle impact rate on the bottom hopper

The effect of the swirler variation on the boiler furnace heat transfer was assessed by calculating the average gas temperature value in the horizontal sections at different elevations (Figure 11Figure). Plot in Figure 11 shows that the 25° swirler setting leads to significant differences of gas temperature profile in comparison with the nominal setting, particularly in the burner region. Conversely, the reduction of swirler angle to 35° does not introduce significant differences in the gas temperature profile.

In summary, the analysis highlighted that the reduction of the swirler angle from 45° to 35° can reduce the particle impact rate on the bottom hopper without appreciable effects on the boiler heat transfer.

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[1] The impact rate is a local parameter indicating the mass of coal particles impacting on the surface per unit time (kg/s). In order to have a global indicator, the impact rate was integrated over the entire bottom hopper surface.

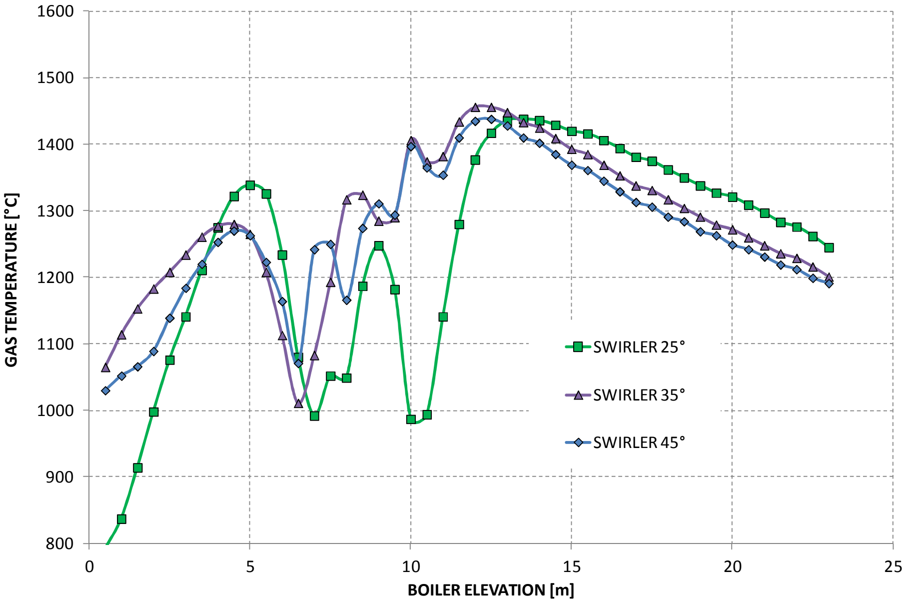

Figure 11 – Effect of the burner swirler setting on the furnace gas temperature profile

The computational analysis took into account also the effect of the coal flow balance between the two burner levels. As the major contribution to the coal particle flow to the cold hopper zone is provided by the bottom level burners (see Figure 12), it is plausible that the reduction of the coal flow to those burners can lead to a reduction of the probability of slagging accumulation.

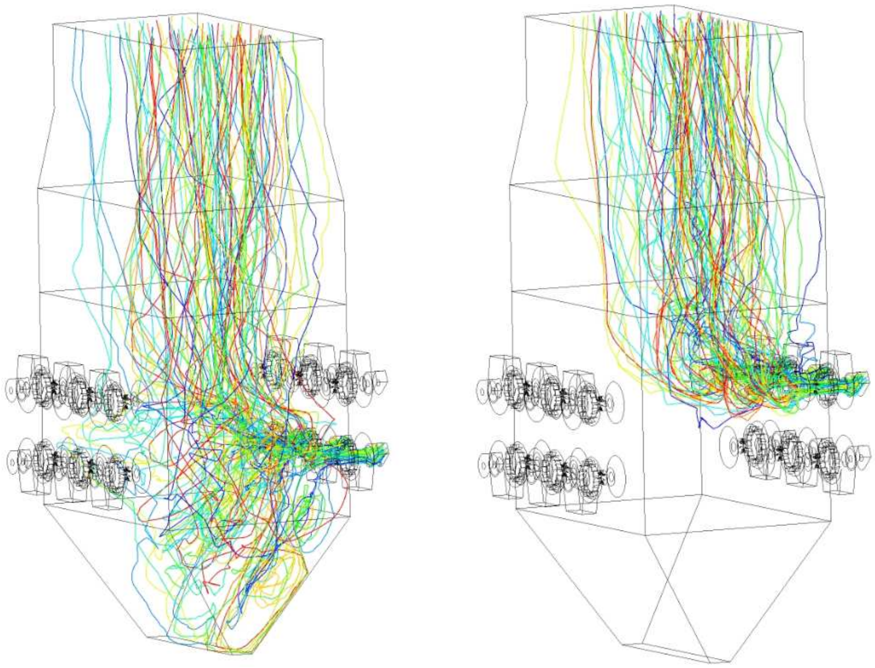

Figure 12 – Streamlines of coal particles injected from all burners (left) and from upper burners of one mill (right)

In order to assess the effect of the coal flow distribution between the two burner levels, several configurations with different coal split bias were investigated by keeping the total coal flow unchanged. Plot in Figure 13 shows that the reduction of the coal flow to the bottom burners leads to a significant reduction of the particle impact rate on the bottom hopper.

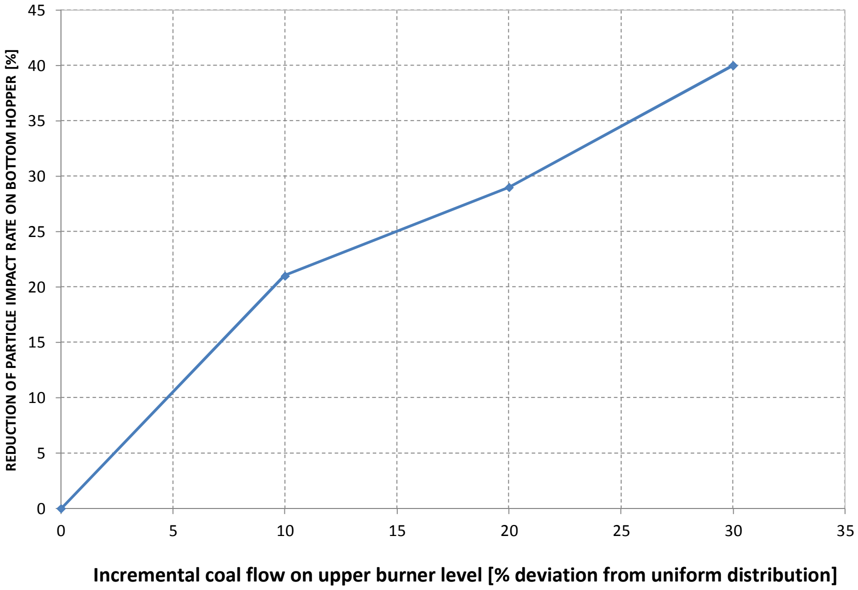

Figure13 – Effect of the coal flow split between the burner levels on the reduction of particle impact rate on the bottom hopper, 4 mills in service

In order to preliminarily assess the applicability of this configuration to the real operation of the boiler, the effect of the coal split on the average gas temperature profile was calculated (Figure 14), keeping unchanged the air flow distribution among the burners, assumed to be uniform.

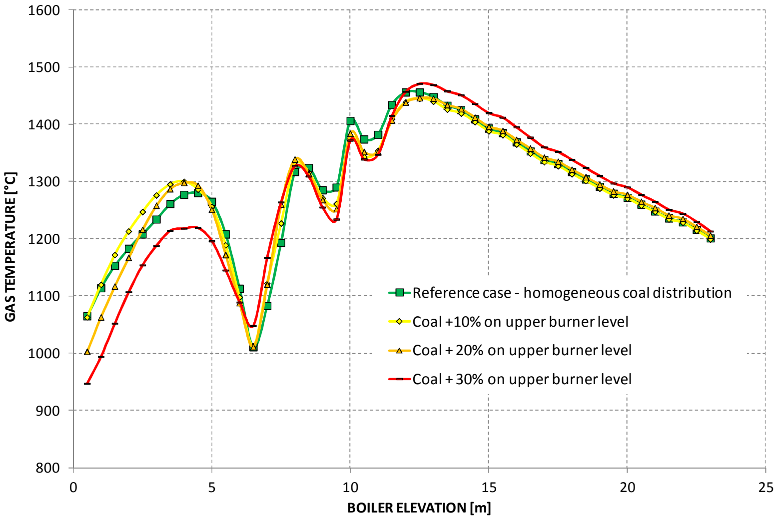

Figure 14 – Effect of the coal split between the burner levels on the gas temperature profile

Plot in Figure 14 does not evidence a relevant effect of the coal split between burner levels on the boiler gas temperature profile.

By summarising, it can be stated that the analysed configurations featured by a higher coal flow in the upper burner level can potentially lead to significant benefit in terms of coal particle impact reduction in the bottom hopper and they are experimentally verifiable in the power plant, without risk for the boiler operation in terms of steam temperature and attemperation need.

Laboratory coal analyses

A long term monitoring of coal and ash characteristics has been conducted by performing detailed analyses on coal samples taken from the coal feeders of some 300 MWe units. In particular, the samples have been collected according to two different procedures:

- on a routine basis, around 4 samples per week;
- selectively, in presence of incipient slagging phenomena in one of the boilers.

The scope of the analyses was the investigation of the variability of coal supply and the research of the influence of ash characteristics on the slagging phenomena, when they take place.

Concerning the influence of the ash characteristics on the slagging phenomena, starting from April until November 2014 all the collected samples have been sent to the Vukhin Institute of Ekaterinburg for a deeper analysis mainly focused on the ash composition, which is the most relevant information for the evaluation of the slagging tendency.

The results from Vukhin Institute have been utilized by ENEL Research for a detailed calculation with the thermodynamic code Fact-Sage™, in order to estimate the equilibrium composition of a multiphase mixture of oxides in both oxidizing and reducing atmosphere, giving as output the melt fraction of the mixture (indicated as slag fraction) as a function of gas temperature.

The main outcomes of the analyses, covering in total more than 100 samples, are summarised in Figure 15, where the curves of slag fraction as a function of temperature, in both oxidizing and reducing atmosphere conditions, have been reported for some samples collected in proximity of slagging events (the red dot indicates a shutdown for deslagging).

In case of June 2nd event the correlation with the ash characteristics has a strong evidence. In that sample the Fe_2O_3 content was higher than 7% and MgO higher than 12%, against typical values of 4-5% and 1-3% respectively. For the other events the correlation is not so evident, but in any case the presence of samples with high slagging propensity as the one of June 2nd demonstrates that, once that the deposit (for several reasons) starts to form, the growth rate can become very high depending on the ash characteristics.

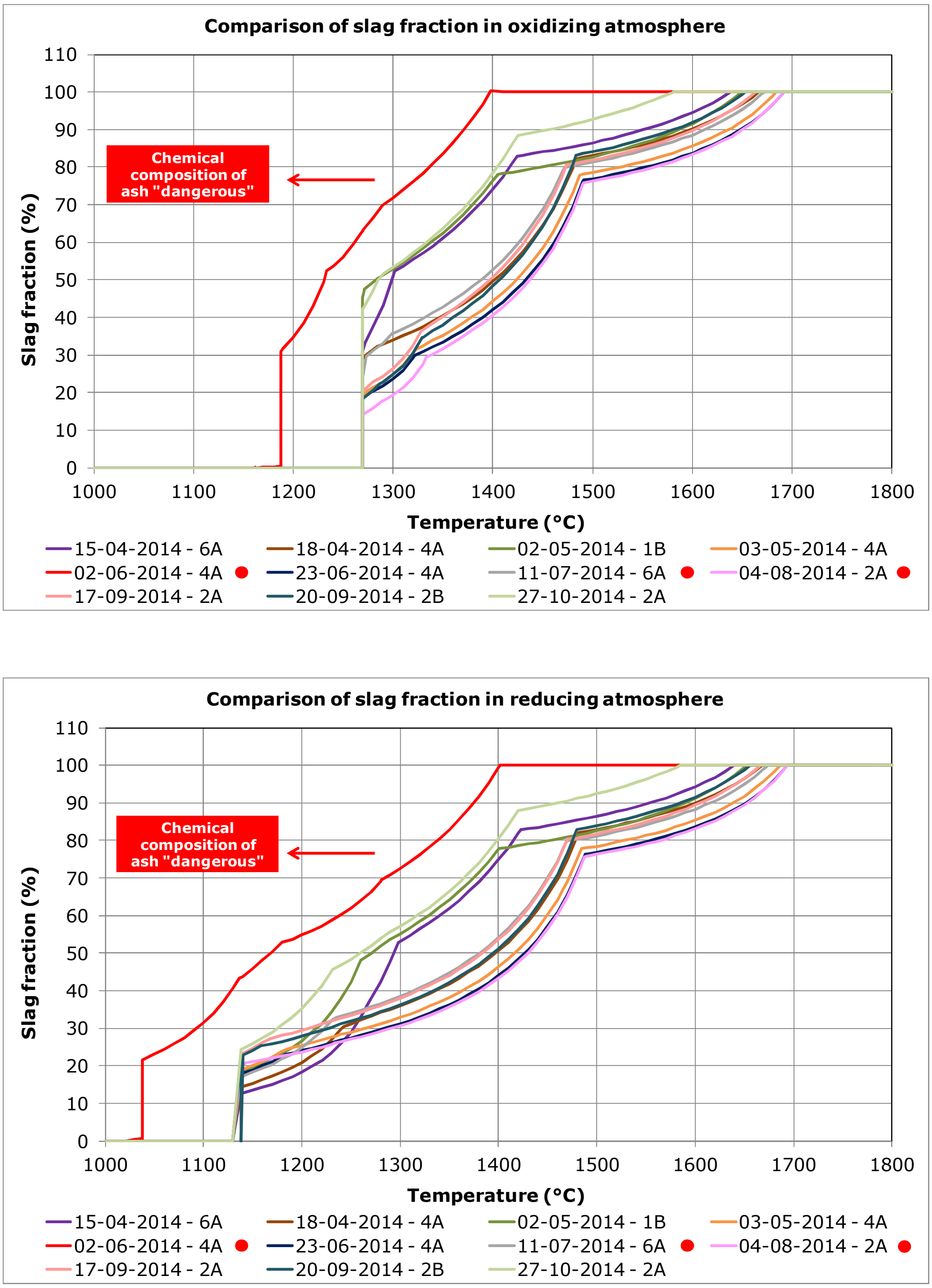

Figure 15 – Slag fraction (%) obtained with Fact-Sage™ code, in oxidizing and reducing atmosphere

Analysis of slagging root causes

Considering all the aspects analysed in the study, a possible mechanism for the activation of the slag deposition phenomenon can be outlined. The start of the deposition is probably due to a difficulty in the ash discharge process caused by a physical obstruction (for example due to a misaligned tube), which can bring in a short time to the formation of a deposit with a thickness of about 3-4 cm. Considering that in the slag (with the heat transfer conditions of the hopper) a gradient of around 200 °C/cm can be easily established, starting from a temperature around 400°C at the surface of the steam tube, the surface temperature of the deposit can reach values of 1000-1200 °C.

If the ash does not have a high slagging propensity and the rate at which it is accumulated in the hopper is not very high, the problem can be overcome by manually removing the obstruction. If the characteristics of the ash have a high slagging propensity, like the one of the sample collected on June 2nd, the growth rate of the deposit can become very high and also the surface temperature of the deposit, causing a rapid increase of the slag fraction (see Figure 15), with a strong boost of the deposit capability of entrapping more particles.

The deposition process can be favoured by operational conditions, such as the increase of coal flow admitted at the lower burner level (because one upper level mill is out of service, or the coal flow indicators are largely wrong), which leads to both an increased particle flow to the hopper and to a reduction of the local stoichiometry, which in turn is favourable to slag formation. Moreover, there can be burner fluido-dynamics conditions (in terms of secondary air swirler position) that can increase the flow rate of solids to the hopper.

In summary, the presence of several factors at the same time can increase the slag growth exponentially, producing the situation shown in Figure 2.

Conclusions

A comprehensive study has been conducted on the phenomena of slagging deposition in the boilers of the 300 MW units at Reftinskaya power station, following three main research lines:

- monitoring of the coal and ash characteristics, their variability and slagging potential;
- data collection during dedicated field tests and plant operation monitoring;
- analyses carried out by means of mathematical modelling: a 1-D model (PROATES™) of the entire boiler, a 3-D model (Fluent) of the combustion chamber and a thermodynamic model (Fact-SAGE™) for the assessment of the ash behaviour and its slagging tendency.

A possible mechanism for the slag formation and growth has been suggested, involving the following aspects:

- influence of hopper tube layout and state of maintenance;
- quality of coal supply;
- boiler operating conditions.

To mitigate and possibly resolve the problem some actions could be undertaken.

1) Concerning the hopper tube layout, a possible solution is to change the layout from horizontal to vertical. This intervention can give very good results, but it requires a deep change in boiler layout, including the repositioning of the air fans. It can be considered for the boiler's environmental rehabilitations, which will be carried over a time period of several years

2) Monitor the coal supply, by putting more stringent limitations on the ash characteristics, particularly Fe_2O_3 and MgO content. The installation of on-line monitoring instruments can be also considered for this purpose

3) Put more attention to the boiler operating conditions, by monitoring the effective combustion conditions and trying to maintain the ratio of air to coal as uniform as possible to the different burners, eventually installing dedicated instrumentation

4) Install devices to control the slag growth actively, by monitoring the real-time formation of the slag and consequently act to clean the area at an early stage. A possibility to monitor the slag deposition might be realized with devices such as infrared cameras, although it should be verified the quality of the signal in an environment with very high dust concentration, while the cleaning could be done with a powerful medium like a strong water jet.