INVESTIGATION OF PRESSURE PULSATIONS IN THE FURNACE AND FLUE GAS TRACT OF THE PULVERIZED COAL COMBUSTION UTILITY BOILER

by

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The paper presents new experimental method developed and new measuring system developed and installed into flame-gas tract of utility boiler. Investigations have been performed at the steam boiler of unit 2 at TPP "Ptolemais", Ptolemais, Greece, which suffered from very unstable combustion and great pressure oscillations. Experimental method, based on high-speed acquisition system, was developed and used for detection of pressure oscillations and determination of the origin of boiler unstable operation. Signals were obtained from piezoelectric pressure sensors located along the flame-gas tract of the steam boiler and time and frequency domain analysis were used for post processing of collected data. Investigations of the pressure oscillations in boiler gas tract have contributed to reveal origin of the boiler unstable operation, and have been of the great help in establishing proper boiler operation.

Key words: *utility boiler, pulsatile pulverized coal combustion, pressure pulsations, time and frequency domain analyses*

Introduction

TPP "Ptolemais", Ptolemais, Greece unit 2 (125 MW) steam boiler was designed for burning low heating value coal – lignite with Hd 7000 kJ/kg. Boiler furnace, with octagonal cross-section, is supplied with air-pulverized coal mixture by six burners. Burners are positioned in such way that air-coal mixture flow streamlines represent tangents of imagined circle at the center of the furnace. The furnace is very compact and its end is at the level of 32 m. Unit is in operation since 1962, but in order to extend operational life and improve unit's performances extensive rehabilitation program was provided at year 2000.

During the initial operation of rehabilitated boiler, serious difficulties and limitations have been experienced. At the beginning, high flame instability and fire pulsation were present even with oil support at high load. After serious efforts to improve boiler operation, design

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steam generation capacity has been finally achieved without fuel oil support. Unfortunately, flame instability was not reduced, presenting, together with reduced thermal efficiency, one of the major problems for the further boiler operation.

To improve this situation refractory belt in the area of burners was installed in February 2001. As the result, boiler has become capable to operate at broader range of steam capacity (240-385 t/h) with noticeable reduction of flame instability and pulsation. Some other important discrepancies from boiler designed operation data have become even more distinguished after installation of burner refractory belt. Namely, higher furnace and boiler exit flue gas temperatures, high losses with unburned combustible matter, *etc*., characterized boiler operation. For sure, refractory belt has broth some improvement, but evidently did not eliminate the origin of flame instability and intensive pulsations.

During October 2001 extensive complex measurements were performed at unit 2 boiler in attempt to detect the source of combustion instability and pressure oscillations. Specially designed equipment and new measuring method were used for that purpose [1-3].

Description of experimental method

The experimental method, based on high-speed acquisition of signals from pressure sensors, is specially developed for measurements at unit 2 TPP "Ptolemais", Greece.

Since unstable combustion was characterized with massive and frequent changes of pressure inside the gas tract, 9 piezoelectric pressure sensors were placed at the specially adopted openings along the boiler tract (Siemens, model KPY32R, operating range ±5 kPa).

Sensors were connected to data acquisition system based on PC with 8-channel, 16-bit Keithley's DAS-HRES acquisition card. This card has a direct memory access (DMA) in order to obtain high-speed acquisition and storage of measured values. Sampling frequencies were in the range of 0.1-5 kHz with commonly used frequency of 1 kHz with up to 8 sensors in on-line function.

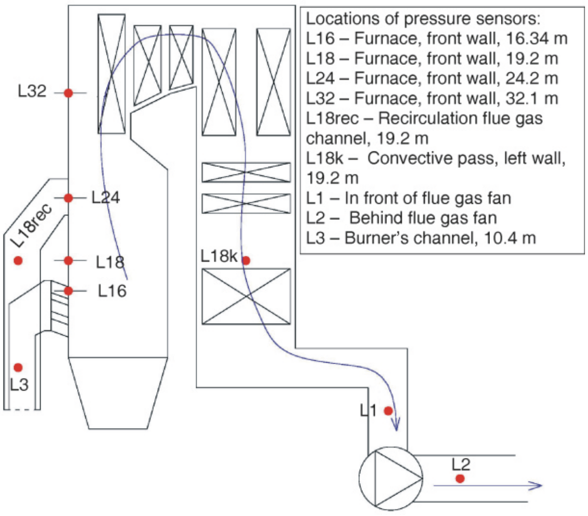

Figure 1. Locations of the pressure sensors placed along the boiler flue gas tract

Sensors were placed at nine different locations in total along the boiler flue gas tract (fig. 1): four placed in the furnace (at levels 16, 19.2, 24, and 32 m – all on the front wall), one in the convective pass (at level 19.2 m – on the side wall), one in the recirculation channel, one in the burner channel, one in front, and one behind flue gases fan [1-3].

Surrounding electrical noises that may be produced by the boiler electrical devices were successfully separated from the main signal using local power supply of sensors and properly shielded conducting lines, as shown in fig. 2.

The most commonly used sampling frequency was 1 kHz and a large amount of data was collected during each of three operational regimes (over $2.4 \cdot 10^6$ data per regime). This amount of data was sufficient for correct time and frequency analysis that fully represent investigated phenomenon.

Considering that pressure waves propagate at the speed of sound (based on the thermophisical properties of the flue gas) and taking into account distance between piezo sensors, sampling frequency of 1 kHz was found to be high enough for representative data recording.

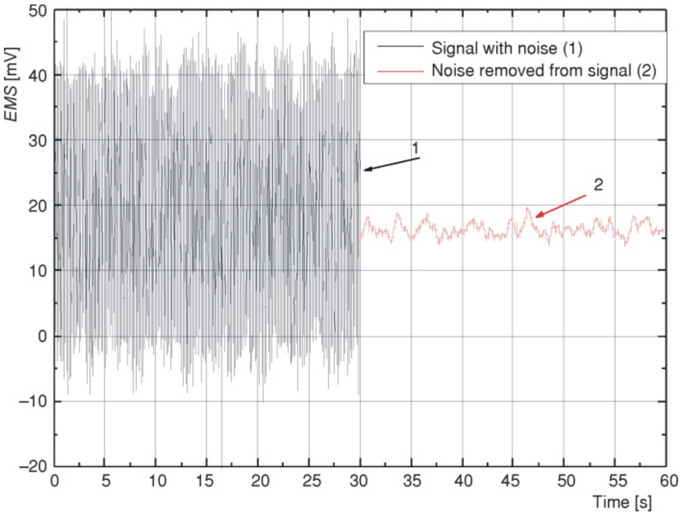

Figure 2. Surrounding noise removing from the acquired signals

Characteristics of the regimes are given in tab. 1. During each operating regime pressure oscillations with different intensities were detected, even in the regime of technical minimum.

Table 1. Main characteristics of the operating regimes

Parameter	Regime I	Regime II	Regime III
Steam production [th^{-1}]	398-404	292-296	403-406
Generator power [MW]	122-125	85-90	124-126
Lignite [th^{-1}] / Air flow [$\mathrm{Nm}^3\mathrm{h}^{-1}$]	206.3/607000	152.8/419000	216.9/574000
Lignite lower heating value [kJkg^{-1}]	6512	6736	6407

Determination of proximal location of oscillation source is possible by measuring time delay between signals recorded by sensors located at different positions along the boiler. Also, fast Fourier transformation (FFT) analysis is conducted in order to find dominant frequency of the phenomenon.

Signals were recorded several times during one operating regime. In this paper results from the first (regime denoted with "a") and the second (regime denoted with "b") of two chosen scans for each regime are presented.

Analysis of the results

Noise was successfully removed from the signals, so recorded signals can be considered as valid representation of measured physical quantity of interest, fig. 3. Several types of analysis were used for post processing of measured data [4-6].

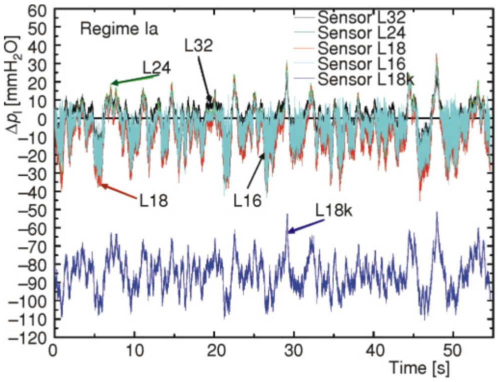

Figure 3. Recorded pressure signals at chosen locations along the boiler, regime Ia (color image see on our web site)

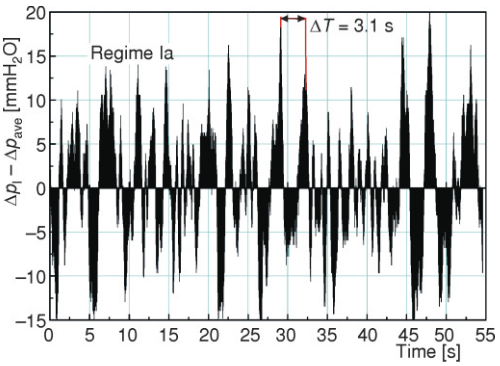

Figure 4. Pressure fluctuations at location L32; regime Ia – peak-to-peak analysis

Pressure fluctuations at location L32 in time, for all three regimes are presented in figs. 4, 5, and 6, respectively. Time period between two subsequent peaks for regime I was around 3.1 seconds (~0.32 Hz), represents the most often frequency of pressure fluctuations during this boiler operation in this regime. For regime II, time period between two subsequent peaks was around 4.6 seconds (~0.22 Hz), and for regime III, around 3.5 seconds (~0.29 Hz).

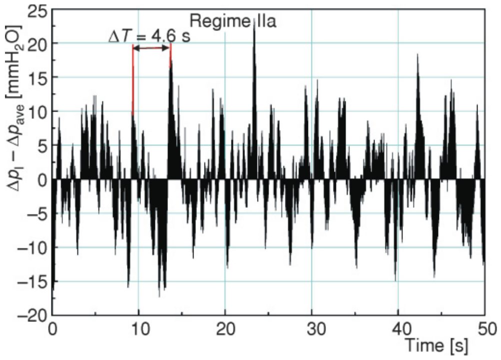

Figure 5. Pressure fluctuations at location L32; regime IIa – peak-to-peak analysis

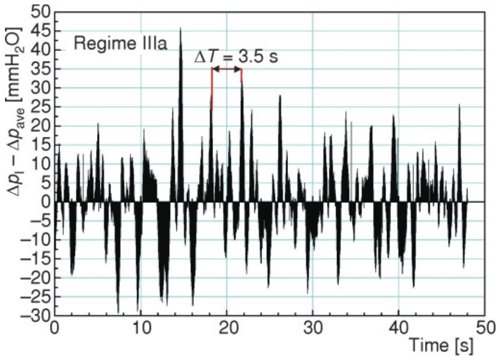

Figure 6. Pressure fluctuations at location L32; regime IIIa – peak-to-peak analysis

In order to determine time delay between signals from different sensors we have to look at enlarged details (one typical peak form of the signal is chosen for this purpose). Time scaled signals from five piezoelectric sensors, together with corresponding low pass filtered values (30 Hz low pass filter was used) are presented in figs. 7, 8, and 9 for regimes I, II, and III, respectively. By analyzing signals presented at those figures one can conclude that pressure signal reaches peak value at the L18 sensor location first, followed with a peak value at the L16 sensor location with a very small time delay (approximately 2-18 milliseconds for different regimes). Signals from the L24 and L32 sensors show larger time delay than signal from L16 sensor, while

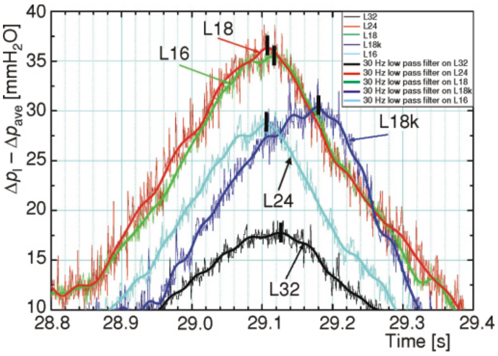

Figure 7. Time-domain analysis; regime I – raw data together with 30 Hz low pass FFT filtered data (color image see on our web site)

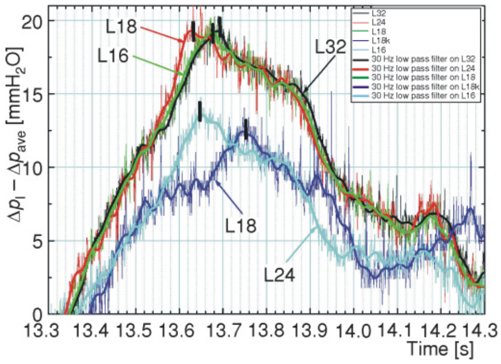

Figure 8. Time-domain analysis; regime II – raw data together with 30 Hz low pass FFT filtered data (color image see on our web site)

peak value of the pressure signal at location L18k (placed in convective channel) has significant time delay relatively to signal at L18 sensor location (approximately 60-90 milliseconds for regime I, 70-120 milliseconds for regime II, and under 50 milliseconds for regime III). This analysis leads to the conclusion that pressure disturbance propagates from the zone just above burners (between sensor locations L16 and L18, fig. 1).

Unfortunately, most acquired signals do not show a well defined peak-to-peak values, but have a random nature. A more generalized method must be used in these cases, called the standard deviation, which expressing the fluctuation of a signal around its average value.

Statistical analysis of signals recorded in all three regimes is shown in figs. 10, 11, and 12. For each presented signal mean value, standard deviation (SD), minimum, and maximum values are given.

Signal at location L18 has the highest amplitude for all operating regimes which can lead us to the conclusion that disturbance origin is closest to this location. Pulsations had maximal intensity of ~0.8 kPa (80 mm H_2O), oscillating about this value from –0.45 to +0.35 kPa for regime I. Maximal intensity for regime II of ~0.5 kPa (50 mm H_2O) has been

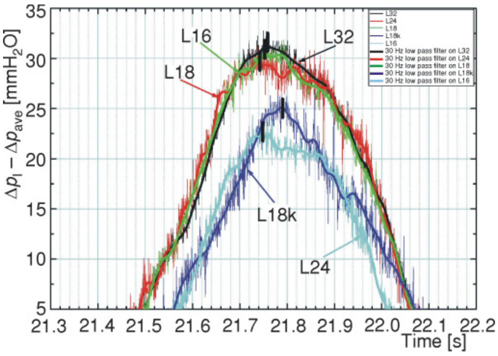

Figure 9. Time-domain analysis; regime III – raw data together with 30 Hz low pass FFT

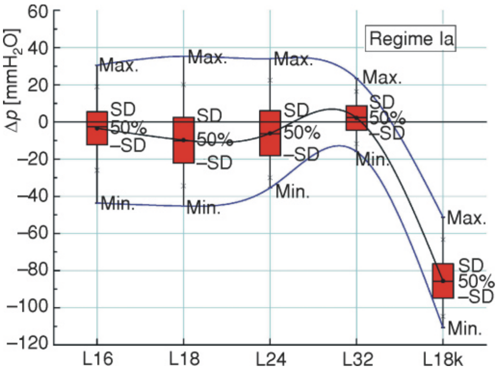

Figure 10. Time-domain analysis; regime Ia – statistical analysis of raw data

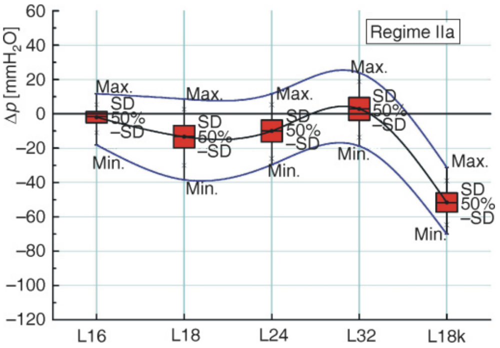

Figure 11. Time-domain analysis; regime IIa – statistical analysis of raw data

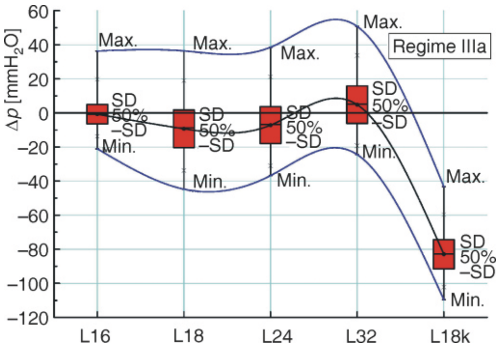

Figure 12. Time-domain analysis; regime IIIa – statistical analysis of raw data

detected, oscillating around –0.4 to +0.1 kPa, and for regime III about ~0.9 kPa (90 mm H_2O), in the range – 0.5 to +0.4 kPa.

Compared to the regime I, pressure fluctuations during regime II are 48% less frequent, the location of pressure disturbances origin is almost the same (the 18 m level in the furnace) and the biggest pressure fluctuations were 60% less. During the regime III, pressure disturbances had the same frequency as during regime I, the biggest amplitude and the very enlarge zone of disturbance origin over the 18 m furnace level.

Conclusions of time delay analyses are confirmed by statistical analyses of intensity of pressure changes in the boiler gas tract, in which the biggest pressure fluctuations are observed in the furnace above burners around the 18 m level.

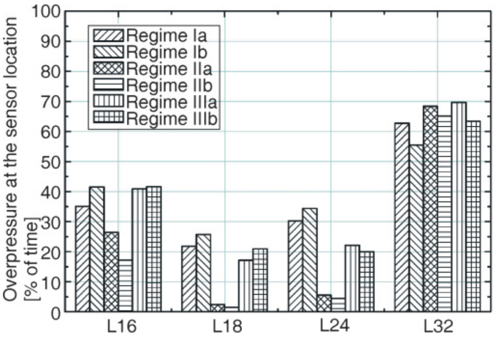

Figure 13. Time-domain analysis; all regimes – pressure over atmospheric in percentage of operating time

During boiler operation in all three investigated operational regimes, overpressure (above the atmospheric pressure) in gas tract takes remarkably long time. Percentage of time while boiler operates under overpressure in its gas tract, are presented in fig. 13 for all investigated regimes and all measuring locations in the furnace.

To present coupled effect of disturbance amplitude and total duration of boiler overpressure operation we derived a dimensional coefficient, defined as:

$$\text{Complex coefficient} = \frac{1}{T}{}_{0}^{T}\Delta p(\tau)\,\mathrm{d}\tau \quad \text{for} \quad \Delta p(\tau) \quad 0 \tag{1}$$

where Δp is the relative pressure measured with piezoelectric sensor and T is the total measurement period. Distribution of this coefficient for all regimes and all monitored locations in the furnace is given in fig. 14.

Distribution of the dimensional *complex coefficient* is very similar to the distribution of boiler operational time under overpressure (compare figs. 13 and 14), indicating that both, the amplitude and overpressure state, are dependent variables related to the investigated phenomenon. Taking all operating regimes into consideration, this coefficient remains in narrow range from location L16 to L24, and has a big increase at L32 location, which is obviously caused by boiler geometry. Looking at the coefficient distribution, it can be concluded that operational regimes I and III are very similar, with somewhat higher amplitude at the highest position (L32) in the boiler furnace during regime III.

The Fourier transform converts a time domain representation of a signal into a frequency domain representation. The energy content of the signal over its frequencies is given by the power spectrum.

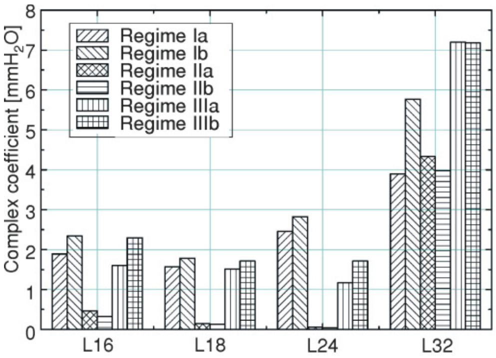

Figure 14. Time-domain analysis; all regimes – dimensional complex coefficient distribution

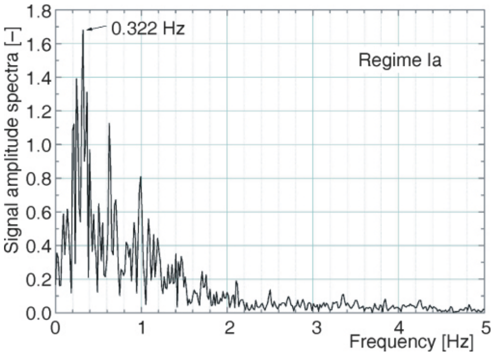

Figure 15. Pressure fluctuations at level 32.1 m; regime Ia – FFT analysis, amplitude-frequency characteristics

Results of FFT analysis for regime I are presented in fig. 15. Peak value, frequency that carries the biggest amount of energy, is about *f* = 0.322 Hz, which exactly corresponds to estimated value of time delay from time-domain analysis.

Figure 16 shows FFT amplitude spectrum of signal during regime II. Several peaks could be found in the spectrum from *f* = 0.214 Hz to *f* = 0.259 Hz. Again, correspondence with time-domain analysis is very good.

Also, good correspondence of estimated frequency in time and frequency domain remains for regime III, fig. 17. Peak on *f* = 0.244 Hz, followed with several peaks up to 1.2 Hz, can be found on FFT amplitude spectrum of taken readings.

In all cases significant amplitude values are distributed along frequencies below 2 Hz. During one regime, amplitude-frequency characteristic is same for all sensors.

Cross-correlation, as a standard method of estimating the degree to which two signals are correlated, described phenomenon in the frequency domain. Sample cross-correlation *vs.*

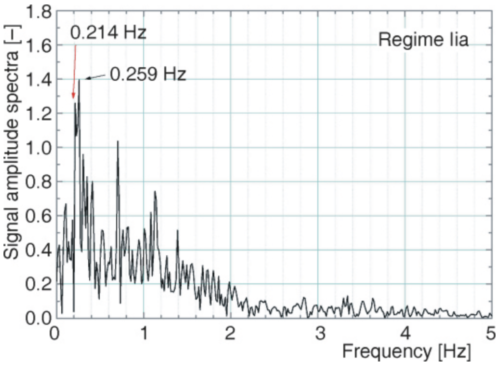

Figure 16. Pressure fluctuations at level 32.1 m; regime IIa – FFT analysis, amplitude-frequency characteristics

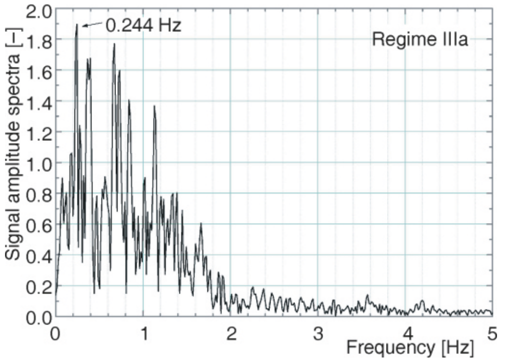

Figure 17. Pressure fluctuations at level 32.1 m; regime IIIa – FFT analysis, amplitude-frequency characteristics

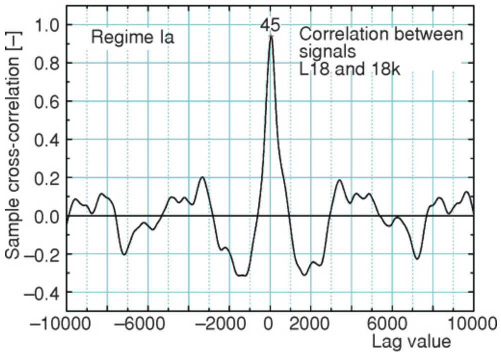

Figure 18. Cross-correlation calculation results; regime Ia – signals from sensors on level 19.2 m in boiler (L18) and in the convective pass (L18k)

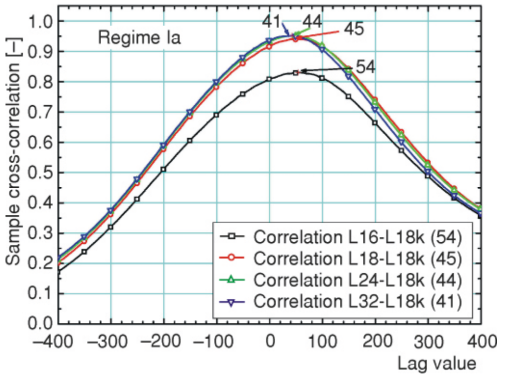

Figure 19. Cross-correlation calculation results; regime Ia – signals from all sensors

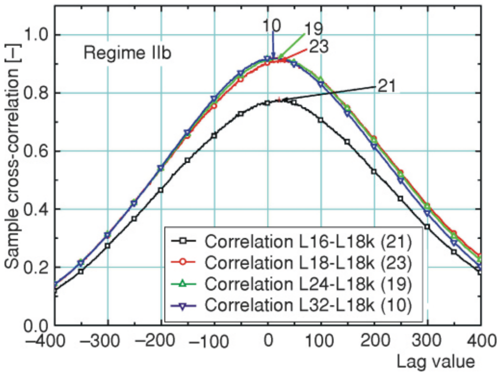

Figure 20. Cross-correlation calculation results; regime IIb – signals from all sensors

lag value, shown in fig. 18, represents cross-correlation between signals from L18 and L18k locations for regime I.

Calculated correlation have very sharp peak at lag value of 45. Positive lag value in this calculation means that first signal used is in front of second; in actual case, L18 is in front of L18k signal. According to the sampling frequency used in this measurement, calculated result of time delay between two signals is 45 ms. Based on the value of time delay information about pressure wave propagation speed in the volume can be obtained, taking a lot of barriers (such as heat exchangers between two pressure sensors and two-phase high temperature flow in the boiler) into account.

Cross-correlation between all other pairs of signals (between all sensors in the furnace and sensor L18k in the boiler convective pass) confirms conclusion that disturbance origin is in the volume above burners (figs. 19, 20, and 21). During regime III time delay between all signals from L18 up to L32 has the same value, leading to the conclusion that disturbance origin zone is significantly enlarged during this operational regime.

Conclusions

Presented experimental method for complex investigation of pressure oscillations in steam boiler no. 2 TPP "Ptolemais", Greece, has given good and useful results, although it was used for the first time in industrial conditions. Quality of recorded signals was surprisingly good with surrounding noise removed.

Large amount of collected data represents solid base for detail analyses, both in time and frequency domain. Applying above mentioned analyses on data collected in all regimes, several qualitative conclusions representing investigated phenomenon are obtained.

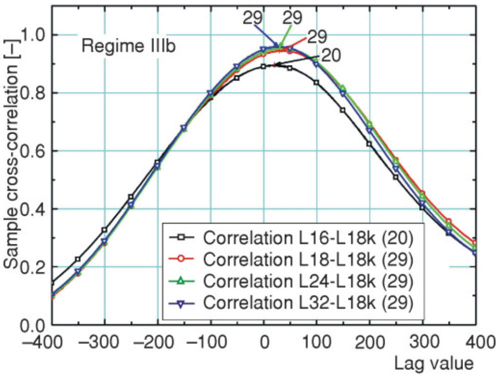

Figure 21. Cross-correlation calculation results; regime IIIb – signals from all sensors

Estimated time period between two subsequent peaks was changed from regime to regime and it took a value ΔT 3,1 s in regime I, ΔT 4,6 s in regime II, and ΔT 3,5 s in regime III. FFT spectrum for investigated regimes shows peaks at $f = 0.322$ Hz, $f = 0.214\text{-}0.259$ Hz, and $f = 0.244$ Hz which corresponds very good to results of time delay in time-domain analysis.

Analysis of the characteristic peaks scaled in time, shows very similar behavior in regimes I and II, while regime III shows different pattern. In regimes I and II pressure signal reaches peak value at the L18 sensor location first, followed by a peak value at the L16 sensor location with a very small time delay. Signals from the L24 and L32 sensors show larger time delay than signal from L16 sensor. Analysis of regime III shows that there is no significant time delay between signals from sensors located in boiler furnace. This can lead to conclusion that in this regime area of disturbance origin is significantly enlarged, so it affects all sensors in furnace at the almost same time. In all investigated regimes peak value of the pressure signal at location L18k has significant time delay relative to signals in the boiler furnace, which can be expected regarding to its position (boiler convective pass) and disturbance propagation direction from the furnace to the boiler convective pass.

From statistically treated data, in regimes I and II, signal at level L18 has the highest amplitude, which can lead to the conclusion that disturbance origin is closest to this location, while in regime III amplitudes of all signals from L18 to L32 are remarkable enlarged, except for sensor at location L16, which can be explained by redistributed mass flow rates in the burners (this sensor is located just above the burner and is mostly affected by this flow redistribution).

The boiler furnace operates remarkably long time in over pressure at all monitored locations in regimes I and III, but also in regime II.

Successful application of this experimental method that was contributed to determination of location, intensity, and frequency of pressure disturbances in addition with the results of other complex tests: milling system tests, thermal tests of furnace, and flue gas fan tests [7] that were simultaneously performed, was of great help in achievement of stable boiler operation. Milling system tests have shown that pulverized lignite from all tested mills was coarser than designed. Also, residual moisture content in pulverized lignite was found as much higher as designed within all mills tests.

Finally, can be concluded that due to not proper mills operation volatile matters stay captured in coarse milled and wet lignite particles. Instead of fast and continual ignition and combustion of volatile matters, which enables easy ignition and stable combustion of solid combustible matter, prolonged heating and drying of large and wet lignite particles takes place in the burner zone, while volatiles combustion is dislocated to the upper boiler zones.

Processes of heating, drying, and evaporation of volatile matters are time consuming, so, above the burner zone, significant volumes of the very specific mixture composed of: volatile matters, fine combustible particles, and flue gases permanently arise. Very fast ignition and combustion of those discrete volumes, enriched in volatile matters during the time, is similar to explosion responsible to unstable combustion in the utility boiler.

By applying some suitable measures, mainly the adjustment of milling system, burners and fresh air blowers, the problem was almost completely solved, and the unit reached a nominal power, followed by designed parameters during stable operation.

Nomenclature

EMS – signal voltage, [mV]
f – frequency, [Hz]
Hd – low heating value, [$\mathrm{kJkg^{-1}}$]
Δp – relative pressure, [$\mathrm{mmH_2O}$]
ΔT – time period between two subsequent peaks, [s]
τ – time, [s]

Subscripts

ave – average value

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