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Une approche sonique pour la mesure de la température des gaz dans les chaudières de grande puissance

La mesure de la température des gaz dans la chambre de combustion des chaudières de grande puissance a un rôle clé pour la personnalisation des installations, et elle peut avoir un impact immédiat sur le fonctionnement correct, et sur les coûts durant la vie du compresseur. On comprend facilement que la notoriété environnementale et l'environnement empêche d'appliquer toute méthode qui n'était pas interne à la messure, qui ne pourrait pas être entrepris que dans des périodes très courtes et qui ne pourrait être considéré comme un moyen de surveillance à long terme. En outre, les techniques optiques n'ont pas donné jusqu'ici les résultats espérés, en raison des problèmes liés à l'impact de gaz aux distances très éloignées et à l'impact de coussinets de ventilation. Par ailleurs, les coûts sont très élevés, et l'élimination des problèmes considérables d'interférence.

La méthodologie est basée sur la mesure du retard d'un signal acoustique à longue durée nominale de la sonde de température entre deux capteurs faisant face aux parois de la chaudière. Une température moyenne sur chaque trajet est obtenue. Une autre sonde thermique sur la section de mesure peut alors être utilisée. Actuellement, la sonde acoustique n'arrive pas à être utilisée dans la solution possible pour la surveillance à long terme. Mais les deux problèmes majeurs font passer le temps où une solution est possible.

a) l'extension des mesures de la température dans de grandes chaudières n'est pas encore possible
b) l'interprétation des données sur les parois de chaudières demandant de trouver une méthode adaptée

En conclusion, le travail des chercheurs décrit dans cet article a porté principalement sur les deux problèmes mentionnés ci-dessus.

The paper describes the recent improvements of a proprietary system for the estimate of temperature distribution inside gas flows by sonic methods, with special attention to applications in the steam boilers of power stations. In particular, together with a short review of the original configuration, the problem of installation and protection of the measuring instruments is first discussed and the newly developed solutions are shown. Then the revision of the signal processing algorithms, employed for the determination of the temperature along the transducer paths between any two transducers, is described, the aim was to reduce the scattering of the measurements, and to improve their reliability, despite of the strong levels of background noise and the highly oscillatory system under measurement.

The results obtained are validated by preliminary tests carried out on a coal fired 660 MW steam boiler are documented in some detail.
The measurement of the low temperature in the furnace of power boilers has a remarkable interest for the plant personnel, since it can have immediate impact on the correct operation and on the life expectancy of the components.

In fact, the gas temperature knowledge is important for fuel and air balancing, for optimizing the burner operation, for keeping the fireball off the walls in order to prevent wall tube fritting corrosion, for the control of the emissions, for pointing out possible reductions of heat exchange caused by dirt on the tubes, for verifying vitrification of combustion residues due to threshold temperature overcomings and, of course, for the computations of residual life of the materials.

All these aspects assume even more prominence for the innovative "Ultra-Hyper-Critical" (UHC) cycles, with a working range of steam temperature up to 720°C and 400 bar pressures.

It is easily understood that the extreme harshness of the furnace environment prevents from applying any kind of intrusive measurement system, that cannot be applied not for very short times and that, by no means, can be considered for long term monitoring. Also optical techniques did not give so far the expected results, because of problems of gas opacity over distances of industrial interest; moreover those systems are very costly and entail considerable maintenance problems.

The sonic method is based on the delay measurement of an acoustic signal on a number of paths between transducers faced to the boiler walls. A mean temperature on every path is first obtained; a thermal map on the measurement section can then be drawn. To the present time, the acoustic gymnastics has turned out to be the only possible solution for long term monitoring. But two major problems did not yet find a satisfactory solution: at the reliability of the temperature measurements on large boilers was not yet acceptable for unsupervised signal processing; at the installation of the probes on the boiler walls still required too large openings, so that it was very much cumbersome and costly, in particular for retrofitting on existing plants, and the maintenance was once again difficult, if not impossible, with the plant in operation.

Therefore the research work described in this paper addressed particularly the two above mentioned problems.

The paper, after a short review of the original system, first illustrates the new solutions for the existing horns, then discusses into some details the signal processing algorithms and finally shows some results obtained from the tests performed on an experimental installation on a boiler of a 660 MW coal fired plant.

The original system and the problems of temperature measurement in industrial boilers

In its original configuration, the proprietary system developed at CESI consisted of a number of dual function electroacoustic transducers, consisted of a compression driver able to emit and receive the signal. Each transducer was provided with local intelligence for signal processing and communicated for control and data exchange with a central server via a field bus. The digital electronic components and the fieldbus are by now somewhat obsolete. Thewavetgates had to be placed beyond the furnace walls and, consequently, they were rather costly, prone to wear, difficult to install and to maintain. A view of the original system is given in Fig. 1.

![Fig. 1: Hardware of the original system](image)

It is well known that the speed of sound $c$ in a gas is a function of the temperature $T$, through the following equation:

$$
c = \sqrt{\frac{kT}{M}}$$

where $k$ is the universal gas constant, $M$ is the molar mass of the gas, $T$ is the ratio of the specific thermal capacities at constant pressure and at constant volume respectively. The generated signal was a fast GS ms sinusoid sweep (chip). The flight time $t$ on the path $d$ between any couple of transducers was determined as the absolute maximum value of the cross-correlation function between the excitation and the received signal. From equation (1) it is apparent that the uncertainties in the temperature estimates are a quadratic function of the uncertainties in the measured flight time.

Averaging the results of a number of subsequent measurements, it is possible to obtain temperature values within an uncertainty range of ±5% of the expected value. When noisy receptors in operation the background noise is exceedingly high and the scattering of measurements becomes in general unacceptable.

There are several additional factors affecting the precision of such kind of measurement, tied to the physics of the problem: gas temperature gradients close to the walls and inside the waveguide; gradients in the flow direction causing curved paths; thermal distillation of boiler; uncertainties in the gas properties. A good summary of the possible errors and of some suggestions for their compensation is provided in [1].

Nonetheless, on the light of the experience gained so far, the greatest source of uncertainty in the measure is likely to be the nonstationary characteristics of the system under measurement, as it is discussed later on. That is due to turbulences of the gas flow, phase component of the gas speed, variable content of impurities.
The new design of the waveguides

The original waveguides illustrated in Fig. 11 offered a satisfactory acoustic efficiency, with an exponential profile and geometric dimensions optimized for the range of emitted frequencies. On the other hand, the manufacturing costs were pretty high, the installation cumbersome and the maintenance difficult and by no means possible with the boiler in normal operation.

![Fig. 2: The new guide waves installed for the tests on the plant](image)

Namely, those guides were not well suited for retrofitting existing plants, because of the obvious difficulties to get the dust from the loudspeaker to pass through the wall tubes, separated from each other by narrow fins, typically as large as 12×16 mm. By the way, this holds true also for commercially available systems, that have horns with circular section and mouth diameters of about 60 mm.

Therefore, the new horn were designed in order to deal with these problems. The transverse section is rectangular so that they can be faced to the furnace from outside.

![Fig. 3: Laboratory test of the new horns: experimental set-up and results](image)

The flame-wall, with a simple opening in the tube fin equal to the mouth area of the horn. A connecting frame was designed so as to make it easier the installation and removal, in a very simple plug-in mode, for maintenance, repair or substitution with the boiler in operation. A plug was also provided to close the opening in the tube wall in the absence of the horn.

Two profiles were designed, one exponential and another trapezoidal, for further simplification of manufacturing. Some stiffening was introduced to avoid excessive structural vibrations. The cost of such horns was obviously very cheap. An example of the experimental installation of the new horns for the tests on the plant is illustrated in Fig. 7.

The small pipe below the horn is the waveguide of the receiving microphone. In later tests, the length of the microphone pipe was shortened and adapted by spacers for better tuning acoustic resonances.

Of course the above improvements have been obtained at the expense of a reduced acoustic efficiency. Some tests were carried out in the laboratory with a mockup of the tube wall in order to compare the emissions of two new horns, the original horn and the bare loudspeaker. The comparative values of the sound pressure levels measured in the laboratory at 3 m distance from the mouth of the horns are reported in the diagrams of Fig. 3.

The new guide emission is in fact a 12-15 dB lower than the original ones in the frequency range from 500 Hz to 2.5 kHz. An unwanted result is also constituted by the repeated acoustic resonances introduced by the new
guides, that can affect the quality of the cross-correlation function. This effect is clearly demonstrated in Fig. 4. All the results of the field tests described in chapter 5 of the paper were carried out with use of the new waveguides just described. A further upgrading is currently under development in order to increase the modal area, to reduce the effect of acoustic resonances, to improve the coupling of the acoustic impedances of the loudspeaker and the horn, while keeping the same advantages of installation and maintenance. This will result in an entirely new design of the horns and of the receiving waveguide.

Some aspects of the signal generation and processing

In the original system, the excitation was constituted by a 10 ms burst of a linear chirp with frequency variables between 1.5 kHz and 4.5 kHz and sampling frequency of 100 kHz. The S/N ratio was very low at very low frequency of interest. Far better results could be obtained by extending the excitation time to 2 s, that was found to be a good compromise between keeping excitation and processing times as short as possible and having enough useful signal energy for the response. A logarithmic sweep was preferred, that is somewhat equivalent to pink noise. The whole buffer of the time samples was then transformed in the frequency domain by subsequent records with an appropriate overlapping, each record in turn was filtered with a 6-pole pass-band filter, with a central frequency updated each time to match the average excitation frequency of the examined record, identified on the electric excitation signal. The width of the filter has to be calibrated taking into account the sweep speed and the expected delay of the received signal. The spectra obtained by the subsequent transformations are finally averaged. In this way, an original digital tracking filter was introduced, simple to implement, very fast, selective enough and not requiring, by converse, delicate synchronizations between excitation and response, that has an a priori unknown time delay. The cross-correlation function is obtained from its frequency domain counterpart, the cross-spectrum. An option was introduced to normalize the plain cross spectrum by its measured amplitude and, additionally, by the coherence function, before to invert-transform to the time domain. It must be added at this point that other excitation and processing techniques were tried. One was the cross-correlation with the inverse filter for obtaining the equivalent impulse response of the system [2], as an alternative to the cross-correlation function, but that did not provide better results.

The measurement of the impulse response was also tried by means of a MLS (Maximum Length Sequence) excitation signal [3], but the results were absolutely unusable; in fact this technique is known to be performing well only with linear, time-invariant systems.

The system is highly dispersive, given the acoustic resonances introduced by the waveguides and because of the time variance, that causes remarkable distortions of the cross-correlation function. As a consequence, the cross-correlation function obtained by back-transformation in the time domain is often difficult to be examined for the search of the maximum. A solution is provided by the Hilbert transform. In particular, the search of the maximum was performed on the squared amplitude of the so-called "analytic function", which is always positive, reduces dramatically the oscillations and enhances the maxima. Additionally, it was shown that it is not advisable to estimate the flight time by the time delay of the maximum point of the cross-correlation function: the detection of the flight time based on the occurrence of a prefixed trigger level improves the stability of the readings and reduces possible effects of reflected paths, which sometimes can produce delayed peaks having larger amplitude than the first one.

An alternative and original approach was also devised, in which the excitation signals were given by very short tonal bursts. The frequency must be precisely chosen in consideration of the resonant frequencies of the waveguides and of the background noise. The time delay is determined once again with the Hilbert transform of the cross-correlation functions. The only cycle (signal and silence) of such excitation is typically set to 200 ms; the optimal length of the signal burst depends on the best compromise between S/N ratio and precision of the readings. Preliminary numerical simulations demonstrated that it is in principle possible to obtain usable results with S/N ratio values of -10 dB (that is, the signal is buried 10 dB below the noise).

Results of the test on the plant

Several tests were carried on 660 MW coal plant, employing the new waveguides and the signal processing algorithms described in the previous chapters. Four access points to the boiler furnace were prepared and used; the measurement section was situated in correspondence with the so-called "nose" of the boiler, approximately at 24 meters above the last row of burners (Fig. 5).

Fig. 5: Measurement positions on a 660 MW boiler

The tests have been performed by means of portable instrumentation, illustrated in Fig. 6, together with the scheme of the measurement. The loudspeakers were compression drivers with a 50 W nominal output power in "continuous" service and 100 W in "continuous program" service, according to the IEC definition; the output impedance was 8 Ohm.
A first set of measurements were taken with the boiler turned off. In those conditions, the only possible problems on the cross-correlation function came from reverberation in the furnace and dispersive effects of the waveguides resonances. To this respect, it is interesting to observe how the selective normalization of the cross-spectrum based on the amplitudes of the auto-spectra of the I/O signals produces a much clearer peak in the Hilbert transform of the cross-correlation function, avoiding ambiguities with delayed peaks, as in the example of Fig. 7 (path 2 >> 1).

With the boiler in normal operation at full load, the measurements of the background noise as received by the microphones at the end of a short pipe plus the spacers at the location 2, without (left) and with (right) rotor blowers in action, are illustrated in Fig. 8. Blue curves are averaged spectra, while the red curves are peak-hold spectra. The peaks are the acoustic resonances of the microphone waveguides. The rotor blowers determine a 10 to 20 dB increase of the background noise, in the frequency range 500 Hz-4000 Hz.
The contribution of the signal against the background noise is documented in Fig. 9 (left), where the peak-Hold spectrum level curve, at a sine sweep in the frequency range 800-3200 Hz emitted in 1 and received in 2 is reported against the spectrum of the background noise (green curve). The coherence function between emitted and received signal is reported as well in Fig. 9 (right).

The contribution of the excitation in the received signal is hardly distinguishable from the background noise level over 1500 Hz; a 10 dB excess attenuation of the signal between 1 kHz and 3 kHz was estimated. In comparison with measurements performed while the furnace was not operating, and probably caused by additional loss caused by turbulence and gas flow.

The coherence function is very poor all over the frequency range; it improves for the receiver at points 3 and 4, the last one only with emission from point 2 (Fig. 10).

2–3 (L) and 2–4 (R).

The effects of the tracking filter with respect to a 500–3500 paper-based filter on the signal emitted at point 1 and received in point 2, with a 2 s sweep in the frequency range 800 Hz–3200 Hz, are illustrated by the sonograms and the Hilbert transforms of the cross-correlation function in Fig. 11.

The tracking filter was effective on noisy signals, but further refinements on the tracking filter quality did not produce any appreciable improvement.
Some experiments of time delay measurement with the sinusoidal sweep excitation are shown in Fig. 12, with emission from point 2 and receiver at point 1 (path 2→1). The upper diagrams represent the square amplitude of the Hilbert transform of the cross-correlation function; the lower diagrams represent the same results obtained after preliminary "normalization" of the cross-spectrum.

It is clearly observed from these few diagrams that the shape of the Hilbert transform is not repeatable and some results are nearly different from the average value, like the sequence 13 in Fig. 12. This holds true for the generality of the tests carried out so far.

The standard deviation of the time delay on the paths 1→2, 1→4 and 2→1 computed on a sequence of 20 sweeps was equal to 12.15% for the paths 1→2 and 1→4 and 14.65% for the path 2→1. The value was equal to 1%. Some of the measurements could be in a 70% error with respect to the average value.

A good post-processing strategy should therefore be adopted for averaging or filtering raw time delay values. Moreover considerations about the physics of the process and comparison of the results obtained from slightly different approaches (pretrigger or absolute measure, phase or normalized cross-spectrum) allow for the pre-screening of each new result.

Typical results obtained with the boiler turned off by means of the constant burst excitation are illustrated in Fig. 13, in which the waveforms of the emitted and received signals on the path 1→2 are those of Fig. 14. In the figure the signals are filtered with a 1/3 octave band filter.

Once again, the quality of the results obtained by subsequent bursts can be clearly different from one burst to another. An example is documented in Fig. 15, where the Hilbert transform of the correlation function is illustrated for two distinct sequences of three bursts, with respect to the received signal on the path 2→1.
The results obtained in terms of stability of the time delay values for the two paths 2→1 and 2→3 are shown in Fig. 16 by the blue line. These graphics show that the average values of ten subsequent bursts at a time, all of them belonging to a sequence of 80 bursts.

Conclusions

The paper discussed the measurement of gas temperature in steam boilers of power plants by means of acoustic techniques.

The aim of the research was the updating and enhancement of a pre-existing proprietary system. On one hand, the development of waveguides simple to manufacture and easy to install and to maintain was particularly addressed; on the other hand, the work was focused on the improvement of the excitation and signal processing algorithms so as to arrive at measurements well suited for automatic processing and, therefore, reliable enough for continuous monitoring.

The new design of the emitting horns resulted in low cost and completely non-intrusive probes, well suited for retrofitting on existing plants and that can be inspected and even disassembled with the plant in normal operation, so as to warrant an easy maintenance.

In parallel, a number of signal analysis algorithms were developed, some of them being completely original. In particular, for the sinusoidal sweep excitation, a real time digital tracking filter was introduced, together with a peculiar weighting of the correlation function and a post processing by the Hilbert transform. Moreover, it was developed an alternative and original method that makes use of short time local bursts, with a peculiar data processing. The new solutions were tested on a 660 MW coal fired boiler. The results examined so far confirmed the viability of the new hardware design and the effectiveness of the signal analysis procedures was demonstrated. Nonetheless, the test pointed out that the signal to noise ratio should be further improved and the effects of the acoustic resonances of the new waveguides should be reduced. Further work is in progress to deal with such aspects.

It is then deemed that the major problem is determined by the time variance of the system under measurement. This intrinsic problem can only be relieved by an adequate postprocessing of the raw data obtained by the time delay measurements.

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