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OBSERVATION OF PARTICLE FLOW AND DEPOSITION IN INDUSTRIAL BOILERS

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Abstract. *The present paper presents results from the flow observation within industrial furnaces obtained using a CCD camera installed in a cooled probe. Results are also presented of the visualisation of deposits in heat exchanger tubes for a black liquor recovery boiler. The results of the observation allowed a characterisation of the area of superheaters in high, medium and low slagging potential. A deposition probe was also used to measure the rate of particle entrainment in both sides of the furnace and these are compared with results from a CFD based numerical model showing qualitative agreement. Results are also presented obtained in a pulverised coal fired furnace. In this case the probes had to be miniaturised and the initial results showed the decrease of the heat flux due to the deposits. Some deposits were also collected for further analysis in an electronic microscope.*

Key words: Particulate matter; Industrial furnaces; Experimental methods

1. Introduction

The measurement of particle deposition in tubes is difficult in an industrial environment. The instrumentation of water tubes (e.g. Valero and Cortés, 1996) is one of the most common methods to evaluate the influence of deposits on heat transfer to observe its change along time. Several probes have been developed to measure either the incident and/or absorbed heat flux. This information is valuable to plant operations once they have to program the use of soot blowers. The development of probes for measurements in test furnaces (e.g. Baxter, 2000) on the other extreme are used to characterise the formation of the deposits in well controlled conditions and include the measurement of heat flux, thickness of the deposits and the surface temperature by optical principles. These techniques however are difficult or impossible to transfer to probes to use in industrial environment. The visualisation of the deposits directly is another technique that can be applied and usually is based on infrared detectors using proper filters to avoid the radiation from the flames and particles entrained.

The present paper presents several simple probes that have been used with a reasonable success to characterise the formation of deposits in two well-characterised industrial furnaces. One is a black liquor recovery boiler with a thermal capacity of 270 ton/h of steam at P = 64 bar, T = 460 ºC, where measurements for the gas composition and temperature were performed in a horizontal plane across the furnace for two different modes of operation corresponding to a rotational or interlaced flow pattern of the secondary air (Fontes et al, 2005). The other furnace considered is pulverised fired from a 315 MWe capacity boiler. This furnace has been characterised with the use of rectangular ports in the front wall and with boosted air in swirled circular ports for overfire air (see respectively Costa et al 2003 and 2006).

The objective of the work carried out is the characterization of the particulate matter flow in the furnace and its consequences for particle deposition. In the next session the probes developed are described. Section 3 presents the general characteristics of the boiler furnaces. The collection of images inside the furnaces is reported in section 4 and the result of particle deposition is presented in section 5. Section 6 presents the main conclusions and discusses the potential for the use of the probes presented.

2. Probes developed

Two types of probes were developed, one to use a normal CCD camera within the furnace and the other to allow for the collection of deposits in the probe and to evaluate the rate of heat transfer.

2.1. Probe for visualization

The objective of the development of the probe for visualization is to allow for an effective cooling of the CCD sensor. Further a light source had to be included in the probe to visualize the deposits in the upper part of the recovery boiler furnace and when the probe was used during a stop period for tube inspection. In the recovery boiler, the ports for inspection are rectangular and the probe was built based on boxes with two tubes, one to feed cooling water and other with compressed air for cooling and to connect the camera cables to a portable computer.

Figure 1 shows photographs from the three probes used for the recovery boiler. The middle one (B) without any light source was used during furnace operation in the lower areas, the first (A) for the upper areas and the third (C) during boiler stops to inspect the tubes. Camera C was cooled exclusively by compressed air.

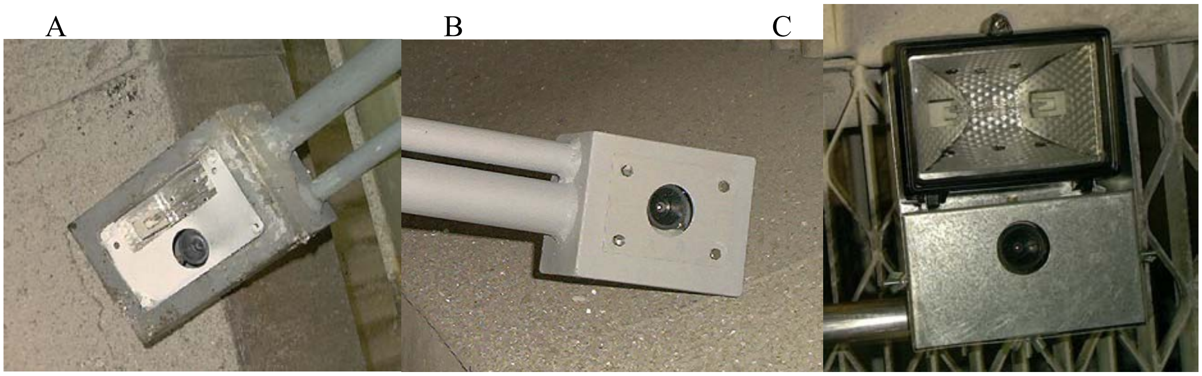

Figure 1 – Photograph of the three cameras developed for the recovery furnace.

In the case of the pulverised coal furnace the ports available for inspection have three inch diameter so a general water cooled probe was built with 70 mm diameter with the possibility to assemble two heads, one for the CCD and other for particle deposition. Figure 2 presents a sketch of the probe tip and a photograph of the probe head.

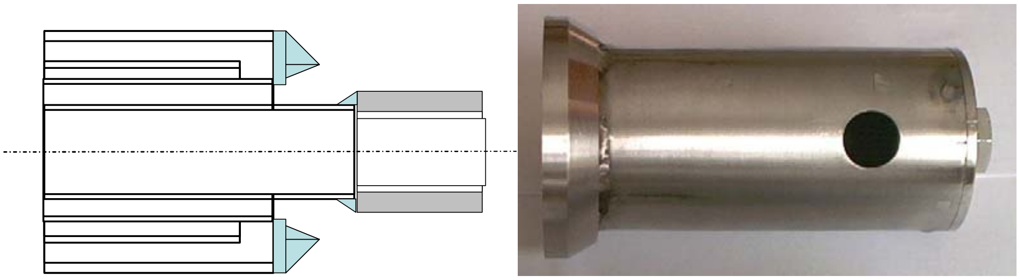

Figure 2 – Sketch of the probe and the probe head with the hole for the CCD camera.

2.1. Probe for deposition

For the recovery boiler furnace the objective was the measurement of the particle entrainment so a rectangular probe was prepared with air cooling as it is presented in figure 3. The probe has a sampling plate with 15x8 cm that can be easily removed from the probe to measure the mass collected. The probe head for the pulverised coal furnace as mentioned was mounted in the same probe shown in figure 2. In this case the head is a closed volume as presented in figure 3 where the location of thermocouples are indicated to measure the wall temperature, the inlet and outlet cooling air temperature and a further thermocouple was used to measure the gas temperature.

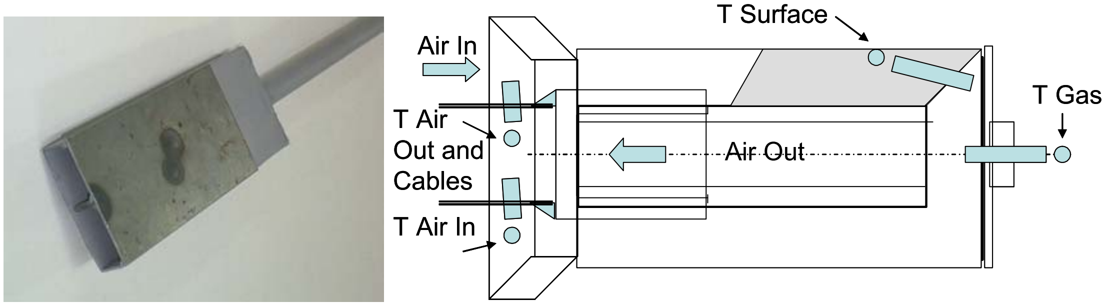

Figure 3 – Photograph of the deposition plate and scheme of the deposition probe head.

3. Furnaces analysed

This section presents briefly the configuration of the furnaces considered in the study so the reader may identify the locations of the visualisation and measurements presented later in the paper. The recovery boiler furnace has a cross section of 9.73mx10.31m and a total height of 41.44 m. The combustion air is supplied at four levels: 1.05m for the primary air, 2,35 and 3,1 for secondary air and at 8.85m for tertiary air, while the black liquor is fed at 5.85m. All are distributed by the four sides of the furnace and the regulation of the flow in the secondary air ports allows the creation of different flow patterns in the furnace, namely a rotational and an interlaced mode.

The observations were made only at the upper part of the furnace close to the super-heaters that start at 27m in level m. There are four super-heaters from left to right in the direction of the gas flow named IA; III; II; IB. The steam is generated in the membrane walls, and the screen and convective evaporator. The screen has also the purpose of protecting the super-heaters. The first sketch in figure 4 shows the upper part of the recovery furnace where the super-heaters are located. Access is possible through the rectangular ports between the heat exchangers.

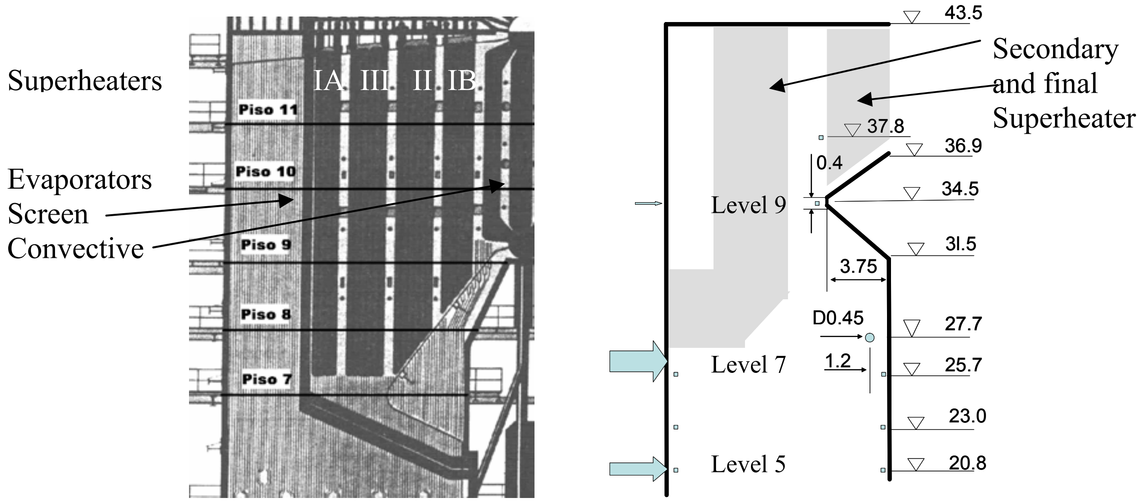

Figure 4 – Schematic representation of the upper part of the furnaces from i) heat recover and ii) pulverised coal.

The pulverised coal furnace cross section is 11.43x15m and the total height is 43.5 m. The burners are located in five rows of four burners in the front wall (from 10.4 m to 10.8 m) and the flow patterns is characterised by a deflection around the burner level 3 upwards in the furnace close to the back wall. The furnace is equipped with staged air supply at level 7 at 25.7 m and then the gases are deflected towards the furnace exit.

The second sketch in figure 4 shows the upper part of the pulverised coal furnace. There are five secondary super-heaters platens and are inspection ports distributed in the front wall to observe them. The other ports are located at the side walls close to the front and back wall. At level 3 and 5 corresponding to the middle and upper row of burners there is also inspection ports at the back wall enabling the observation of the probe inserted into the furnace from the side wall.

4. Visualisation studies

Figure 4 presents a sample of images collected from the entrance of the third super-heater at different levels and using different cameras. As it can be seen the image is more clear for camera C during a stop and during operation camera A provided also reasonable visual information. The image from camera B used in regions of higher temperature was in general poorer due to the interference of hot gases flowing close to the camera.

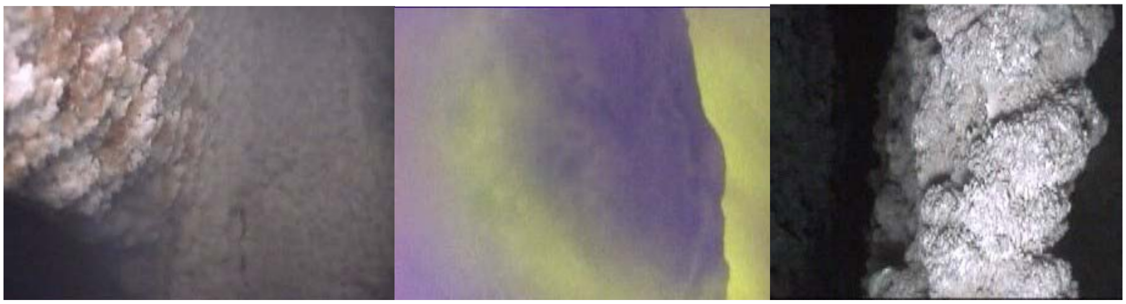

Figure 5 – Deposits in tubes from superheater III
a) Level 10 (Camera A); b) Level 7 (Camera B); Level 11 (Camera C)

From a large collection of images a qualitative evaluation of the effects of slagging in the tubes was elaborated as presented in figure 6. This type of information can be used to operate the soot blowing system selectively.

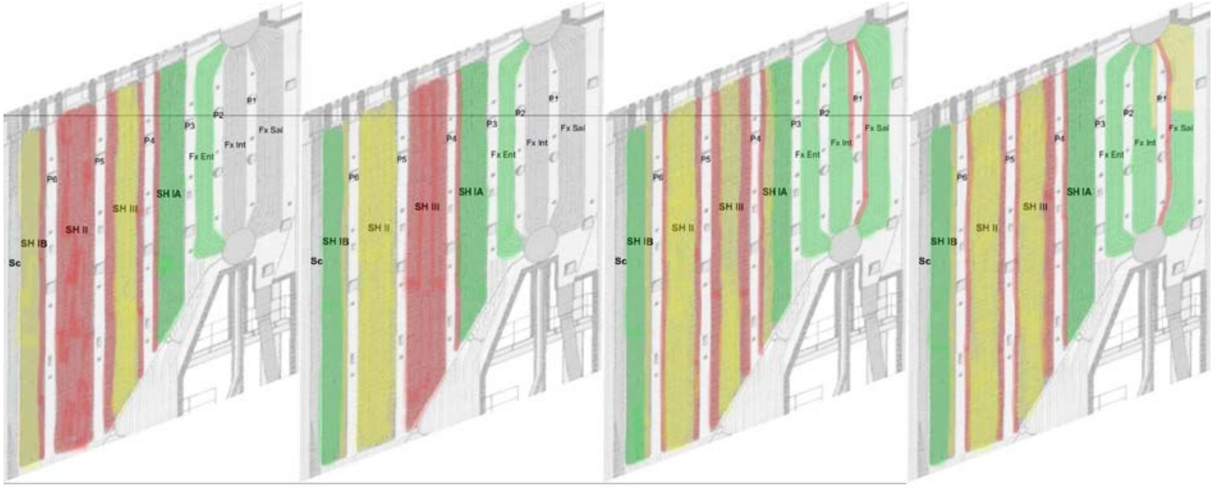

Figure 6 – Classification of severity of slagging in heat exchanger tubes.

The cooling of the CCD camera in the pulverised coal furnace was performed exclusively with compressed air and no damage was observed in the electronic board of the camera. The plastics holding the lenses however were affected during the utilization and therefore the lifetime was limited. The images obtained in the furnace with high air staging were performed in a region with temperatures between 800 and 1000ºC. Figure 7 presents an example of the lower part of the secondary super-heater where the irregular shape of the deposits can be seen and an example of deposits at the tube wall. The tube walls are not prone to heavy slagging so there is little interest in these images. The most interesting region of the furnace to be observed is the entrance of the final super-heater section where temperatures are up to 1200ºC, but no images could be collected due to the overheating of the probe. An improved version with the probe head water cooled is required to access that area.

Figure 7 – Visualization of i)secondary superheater and ii) boiler wall tube.

5. Deposition studies

The deposition probe in the recovery furnace was used to access the rate of particles flow in the two sides of the furnace under different operating conditions. The probe was polished before performing each test. Each test consisted in introducing the plate facing down to the main flow direction and letting it exposed during a fixed time period. After removing the plate from the furnace, the rate of compressed air was increased to produce a fast cooling and avoid further reactions. Then the plate was dismounted and stored in a plastic bag for weighting the collected particles. A mass flux was then calculated simply dividing the mass by the area of the plate and by the exposure time.

Of course some particles deviate from the plate and there will be some re-entrainment but the objective was the comparison of the behaviour in the two sides of the furnace. The particulate matter present in the recovery boiler is a mixture of carbonaceous burning particles and drops formed from the condensation of sodium and potassium vapours. The time for each measurement was a subject of investigation. If this time is to short the errors due to the time to insert and to remove the probe and the small mass of the deposit become more important. On the other hand for large exposition times, the deposits in the surface of the plate may melt and in this case the mass may be partially lost.

Measurements were performed at level 7 (27.6 m) at a distance of 1 m from the front wall. The mass deposited in the plate could be reproduced within 10% when repetitions were done. Figure 8 shows three sets of results from the mass collected in plates in four tests performed in sequence with different time exposures. From this figure it can be observed that the rate of deposition increases initially and then decreases. Plotting the values in terms of rate of deposition allows the observation that the maximum was observed for an exposure time of 3 minutes and thus this was selected for further tests. Measurements were performed in both sides of the furnace for five cases, two in the rotational mode and three with interlaced distribution of secondary air. A summary of the results is presented in table 1, including the black liquor flow rate observed for each case.

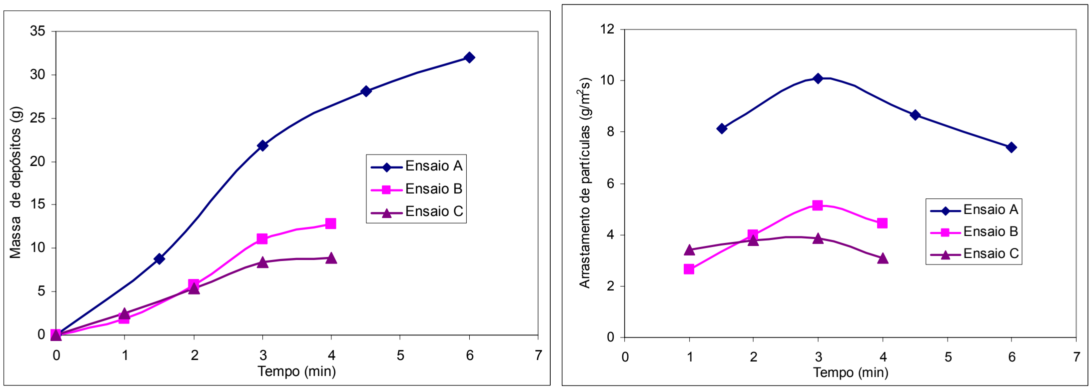

Figure 8 – Mass deposited and rate of deposition in the probe as a function of time.

Table 1 – Rate of particle entrainment captured by the probe. (Values in g/m^{2}s).

	Rotational		Interlaced		
Case Number	14	15	16	17	18
Rate particle deposition Left side (North) (g/m^{2}s)	10.86	9.69	2.92	8.15	4.77
Rate particle deposition Right side (South) (g/m^{2}s)	4.31	4.23	4.81	10.96	8.35
Black liquor flow rate (ton/h)	27.2	26.8	22.0	26.6	25.1

From the table it can be observed that in general the interlaced mode leads to a better balance between both sides of the furnace while in the rotational mode the contribution is higher in the left side. The values depend on many factors including the black liquor flow rate that has a clear influence in the values observed in case 16. CFD based calculations were carried out where particle trajectories were evaluated (Fontes et al, 2005). The interlaced mode led to higher rate of particle entrainment but is more distributed than in the rotational mode as observed. The calculated values for case 14 were 4.14 in the left side and 1.46 in the right side while for case 17 the values were 3.51 and 3.93. Despite the calculated values are less than half the measured ones a good qualitative agreement can be observed which allows the conclusion that in general the rotational mode leads to a lower rate of entrainment but with higher impact in the left side of the boiler (north) as was observed from the visualisation study (See figure 6).

The tube deposition probe was used in two pulverised coal fired furnaces from the Sines power station. The first campaign was performed in unit IV to test the probe and the second in unit I after improving the assemblage. The thermocouples for the measurement of the air temperature in the first version were fixed with cement to the tubes: Inlet in the water cooled part and outlet in the tip of the probe head. The cable for the inlet air temperature had to go through the central tube and back to the location of the air inlet. In the second version the thermocouples were installed in four hole ceramic supports that were mounted in holes as indicated in figure 3. In this case all the cables went through the central tube making the assembling and robustness better. The thermocouple for gas temperature was successfully installed in the first version but the readings were found to be in general lower than measured with a dedicated probe probably due to the plane surface behind, so the reading from this thermocouple was not so relevant. In the second campaign also a thermocouple was located close to the internal surface of the probe head wall to monitor temperature.

Figure 9 shows two typical graphical evolutions of the inlet and outlet air temperature. The graph from the first version in unit IV, presents also the gas temperature while for the second version the wall temperature is also presented. The measurements made from the front wall of the furnace where temperatures are around 800-850ºC and there is lower flow intensity no deposits were observed for different periods of exposition. In this case the temperature difference between the inlet and outlet air temperature remained approximately constant. On the other end for tests made in the ports from the side wall in levels 9, 5 and 3 deposits were formed in the probe and some were collected as shown in figure 10. In the levels of the burners (5 and 3) there are ports also in the back wall that allowed the observation of the build up of 2-5 cm deposits that could not be taken out from the furnace due to the small size of the ports. The second graph in figure 9 shows a decrease in the surface temperature and in parallel a decrease of the outlet air temperature which can be attributed to the decrease of heat extraction by the probe head as a consequence of deposit build up.

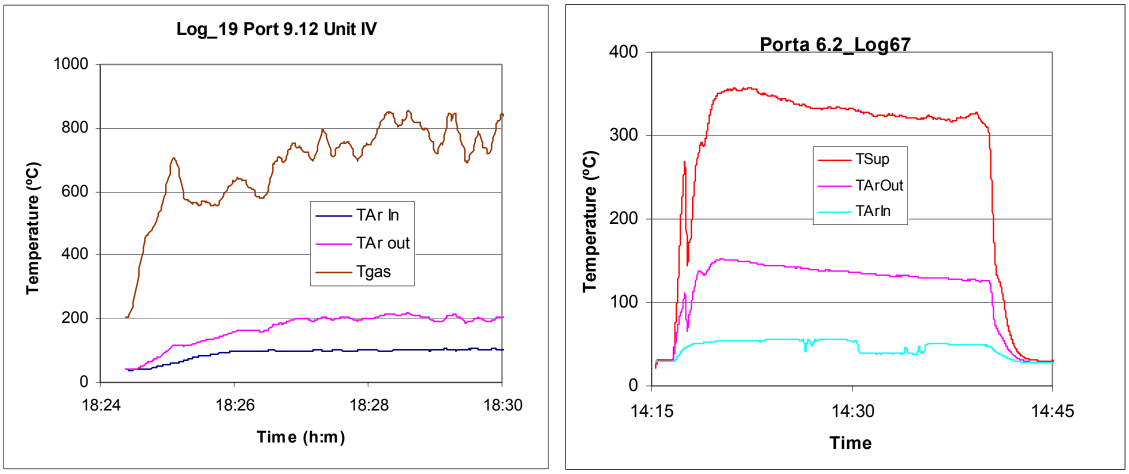

Figure 9 – Temperature evolution in the deposition probe. a) First and b) second versions.

Figure 10 – Photograph of the probe after exposure in the furnace and collected deposits.

Table 2 presents a summary of results from the measurements with the deposition probe, namely the measured temperatures and the calculated heat flux. This value was calculated based on the measured air flow rate and the side area of the tube head. The calculated values are in the expected range once incident radiation may contribute with values in the order of 300 kW/m^2 and the convection contribution may become important for the tests close to the back wall where the flow is higher. In most cases a decrease of the heat flux was observed within 10 to 20 minutes. The higher decreases were observed for the higher surface temperature as a consequence of an easier adhesion on the probe surface. The inlet air temperature was stable in all the period and with a lower value than observed in the first version of the probe showing that in that case the thermocouple must have been displaced. The values in table show also in general that when the probe is further inserted in the furnace leads to higher surface temperature and heat fluxes.

Table 2 – Measured values with the tube deposition probe and calculated heat fluxes in unit I.

Case	48	50	53	54	58	67	68	70	71	73
Port	9.1	9.1	9.1	9E	9E	6.2	6.2	5.2	5.2	3.2
Distance (m)	0.5	1	1	0.5	0.5	1.5	1.5	0.5	1.5	1.5
Temp. Air Inlet (ºC)	49	43	47	47	55	52	48	43	55	55
Temp. Air Out Initial (ºC)	135	136	175	148	290	151	200	157	280	167
Temp. Air Out Final (ºC)		122		176	260	125	165	130	140	
Time of exposure (min)	1	13	1	14	20	20	22	15	4	15
Temp. Surface Initial (ºC)	307	280	550	370	430	355	460	380	625	
Temp. Surface Initial (ºC)		300		295	420	320	460	380	433	
Heat flux Initial (kW/m^2)	228	320	282	372	581	604	629	490	1020	445
Heat flux Final (kW/m^2)		282		466	511	465	484	374	426	

5. Conclusions

The use of a common CCD camera is valuable to reveal information from deposits within boiler furnaces. The collection of images during furnace operation in high temperature areas suffers from interference of the flowing gases. However for cooler areas the images are good if appropriate illumination is provided. The images collected during boiler stops are very good and this probe can be used without cooling water.

The use of a plate to evaluate the rate of particle entrainment was shown to give good qualitative results allowing for the comparison of different firing configurations. The use of a tube deposition probe permitted the collection of deposits samples and showed the influence of operation conditions (gas and surface temperature) on the deposition rate.

6. Acknowledgement

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7. References

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