SURFACE TEMPERATURE MONITORING ON BOILER TUBE BUNDLES

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Abstract. *Internally pressurized tubes are critical components in heat-exchanger application, such as tube bundles in boilers. Those tubes are exposed to high thermal gradients and as a consequence, the material may present creep deformation, even fracture. In the case of Jorge Lacerda Thermoelectric Complex in Capivari de Baixo – SC, most of the breakdowns are caused by creep fracture of boiler tubes, mainly in the final superheater and reheater. The current methods applied to evaluate the surface temperatures of the tubes forming these bundles provide unreliable approximations of the critical temperatures. This paper presents an instrumental apparatus able to measure surface temperatures at the combustion gases flow region inside a boiler. The device consists of a surface temperature sensor attached directly on the tube wall. Different configurations of surface temperature sensors are available, although most of them provide inaccurate results. A new sensor configuration is presented, built with a suitable mineral insulated thermocouple. This shielded sensor is compared to commonly used sensors installed on final superheater and reheater stages on the boiler. Experimental results show that the proposed configuration can provide more accurate results. These new devices were then used to identify the main factors related to high temperatures. This was accomplished by monitoring specific tubes with the new shielded sensors tested under different power conditions.*

Keywords*: Thermoelectric Generation, Boiler Instrumentation, Surface Temperature Measurement.*

1. INTRODUCTION

In the late years Brazilian electrical sector has shown the need of further investments due to the crescent demand in all consumption groups. Besides diversifying the generation sources and the construction of new power-plants, it is important to apply actions aiming to increase the useful life and reliability in the available power-plants. In the case of Jorge Lacerda Thermoelectric Complex in Capivari de Baixo – SC, the frequent unplanned outages in the generating stations are caused by ruptures at boiler tubes. The boiler tubes failures often occur in the superheaters and reheater, after the boiler has operated for a certain period of time. Among other causes, the high thermal gradient is the main cause for these creep fractures due overheating in specific tubes.

The knowledge of tube temperatures becomes then an essential factor to adopt actions to minimize the forced outages. Such tube bundles have been instrumented and monitored by conventional thermocouples attached at an insulated region, distant from the heat transfer area with combustion gases. Actually, this current method supplies only an estimated value for critical temperatures of the tubes. The purpose of this paper is to present an apparatus that is able to provide more reliable results for the surface temperatures of boiler tubes in the combustion gases flow region. It is hoped that the improved evaluation of the high temperatures in the final superheater and reheater devices could provide elements to the better understanding of these accidents.

2. EXPERIMENTAL SETUP AND METHODOLOGY

According to Figure 1, the setup consists of one surface temperature sensor assembly which is composed by a mineral insulated thermocouple connected to an extension cable (type KX) up to a data acquisition unit. A couple of temperature sensors are welded on the tubes surface of the superheater and reheater of a steam generator unit.. Measurements were controlled by a computer interfaced to the data acquisition unit (Agilent 34970A). Since the combustion gases temperature do not exceed 900 ^{o}, it will be used type K thermocouples built with 6mm of outer diameter wires sheathed by AISI 310 stainless steel

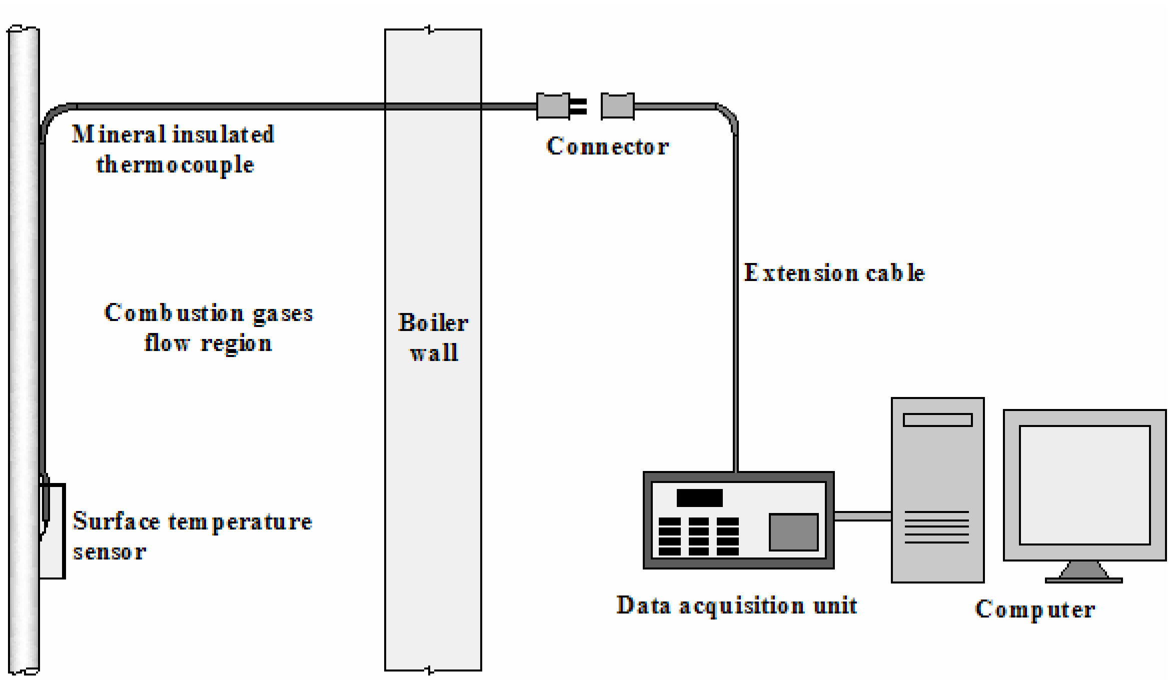


Figure 1 - Temperature measurements system.

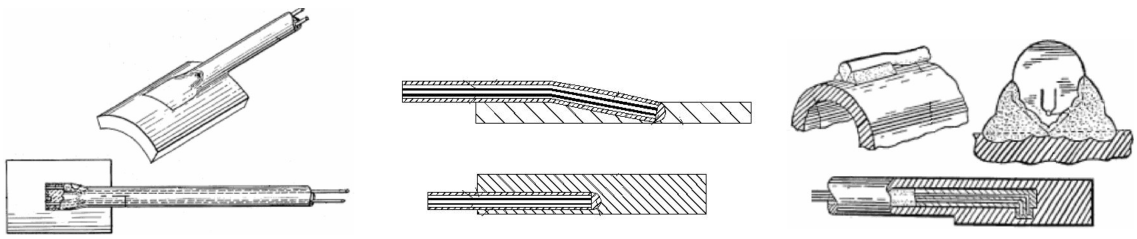
3 A REVIEW ON SURFACE TEMPERATURE SENSORS

Many factors make it difficult to obtain accurate surface temperatures of tube bundles inside the combustion gases flow region, among them, high-temperatures, suspended particulates and radiation heat transfer. Besides, attaching a transducer to a surface is not a simple operation. The measuring device has to be assembled in order to attain the closest value to the real temperature but with minimal disturbance of the surface temperatures, as the presence of the transducer causes a perturbation of the temperature distribution.

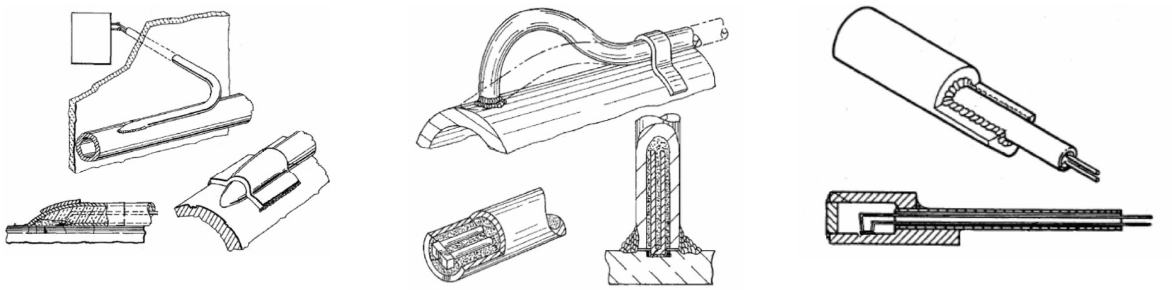
Among the available temperature transducers, the thermocouples are widely applied due numerous advantages. Physically, the thermocouple is very simple, built with two wires welded together at the measuring point. It is flexible, rugged, easy to handle and install, covering a wide range of temperatures. Moreover, its output signal is reasonably linear over portions of that range of temperatures (ASTM, 1974). In order to avoid wire deterioration, it may be used a mineral insulated thermocouple which consists of matched wires surrounded by insulating material (typically oxide-magnesium) covered by a metallic sheath.

At extremely high temperatures, complex reactions may occur between the sheath and the thermocouple wires causing its decalibration. This phenomenon occurs as the mineral oxide layer allows the diffusion of the vaporized materials that composes the metallic parts. Therefore, a correct combination of types of the thermoelements and the sheath should be accomplished to avoid the thermoelectric drift. Regarding its application to boilers, thermocouples type K and N are the most adequate. Bentley and Morgan (1986) evaluated the thermoelectric drift of these thermocouples at temperatures in the range 500-1100 ^{o}C for different sheath materials over periods until 1000 hours. It was observed that at temperatures until 900 ^{o}C, thermocouples K and N sheathed with inconel and AISI 310 stainless steel showed an acceptable behavior. The corresponding drift was not greater than 2 ^{o}C. However, above 900 ^{o}C only type N thermocouples sheathed with inconel must be used to avoid high drift when others materials are used (until -800^{o} C).

Several methods to attach the measurement junction of a mineral insulated thermocouple on a tube surface have been proposed along the years, as shown in Figure 2. They consist of a measurement junction attached in a pad that is directly welded over the tube surface. Such configurations may lead to inaccurate values depending on temperatures levels. In the case of the final superheater and reheater, the combustion gases may be up to 500-600 ^{o}C hotter than the tube surface at the point of measurement. Thus, an excessive heat is absorbed by the metallic sheath and directed to the measurement point of attachment what tend to cause the thermocouple to be responsive to the combustion gases temperature rather than the tube wall temperature.



(a) Hansen (1964) (b) ASTM (1974) (c) Finney (1977)



(d) Granahan and Paulson (1979) (e) Finney (1984) (f) Wannamaker *et.al.* (1992)

Figure 2 - Surface temperature sensors.

In order to overcome such problems a new configuration, called shielded sensor, is proposed that provides a minimal thermal resistance between the measuring junction and the tube wall, as well as to maximize the thermal resistance between the measuring junction and the combustion gases. Accordingly, the thermocouple will respond to the true tube wall temperature and not the gases temperature providing and accurate and reliable temperature readout. To insulate the measuring junction and the thermocouple wires from combustion gases and high temperatures, a thick layer of ceramic fiber is employed.

In this configuration, as shown in Figure 3, the thermocouple wires are stripped from its mineral insulation as it is inserted into the shielded sensor to avoid that the heat flux from the metallic sheath reach the measurement region. The measurement junction is built by fuse-welding the ends of the thermocouple conductors together directly on the tube surface or on a thin sheet surface. The sensor may be installed on tubes using conventional welding, not requiring special operations. The shape of this sensor is unique, properly designed to be mounted on a tube wall, obtaining more accurate readings and increased lifespan.

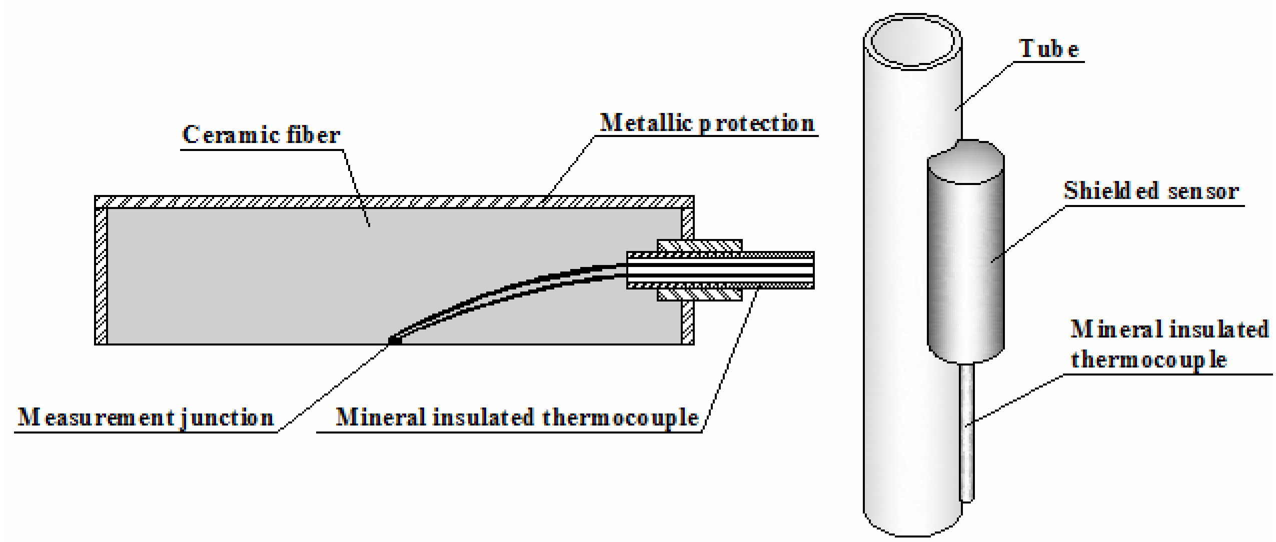


Figure 3 - Shielded sensor.

4 DESCRIPTION OF THE MONITORED REGION

Surface temperatures measurements are carried out on the final superheater and reheater stages of the steam generator in the Thermoelectric Plant, as shown on Figure 4. The figure shows the overall scheme of a typical pulverized coal boiler corresponding to a 131 MW power generation unit.

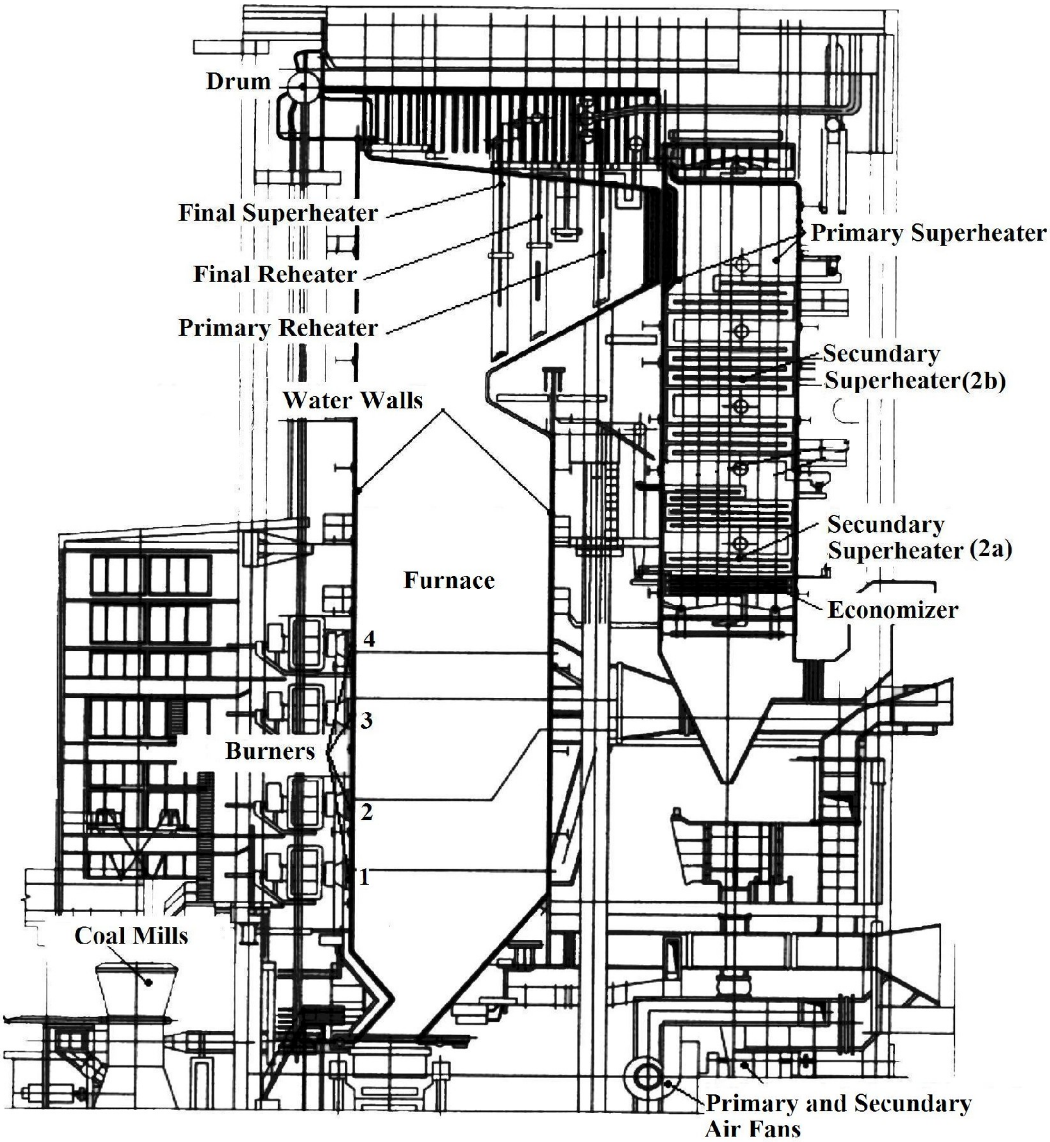


Figure 4 - Scheme diagram of a pulverized coal boiler.

The monitored tubes of final superheater and reheater as well as the respective used sensors are described in Tab.1.

Table 1. Monitored tubes in the final superheater and reheater.

Monitored tubes	Type of sensor
Final superheater - 20º serpentine (*)	Shielded sensor ASTM sensor
Final reheater - 15º serpentine (*)	Shielded sensor ASTM sensor
Final reheater - 38º serpentine (*)	Shielded sensor
Final reheater - 39º serpentine (*)	Shielded sensor

(*) The monitored tubes belong to last row of each serpentine.

The proper installation of thermocouples on the boiler tubes is as important as the adequate combination between the thermoelements type and metallic sheath. It is important to ensure that all surfaces to be joined are cleaned before the welding operation. The TIG (Tungsten Inert Gas) welding process is suggested due its low temperature levels and relative clean weld. The shielded sensor (bottom) and the sensor proposed by ASTM (up) are shown in the Figure 5 after installation on a final superheater tube.

Figure 5 - Surface temperature sensors installed on a final superheater tube.

To minimize the absorbed heat by the metallic sheath one must avoid passing the thermocouple cables through regions that are subject to high temperatures, preferably, close to cool surfaces as for example the water walls. Such procedure prevents the deterioration of the thermocouple structure and increases substantially its lifespan.

It is also important to consider that the exit point of the thermocouple assembly at the boiler wall should have a sliding fit to handle a longitudinal movement. This is caused by expansion and contraction of thermocouple mainly during the start-up and stop of the boiler.

A more detailed scheme of the final superheater and reheater is shown in Figure 6. The final superheater is composed of 40 serpentines made up of 7 tubes each. The external diameter of tubes is 31,8 mm and the wall thickness is 5,6 mm. The final reheater is composed of 78 serpentines made up of 4 tubes. The external diameter and wall thickness of tubes are 44,5 mm and 3,6 mm respectively. Both tube bundles are built with tubes of ASTM A213-T22 steel.

As shown in Figure 6, the temperature monitoring devices are immersed in stagnant air at 300 ^{o}C. As the tube temperature is hotter than air, the tubes are cooled by natural convection. To evaluate the surface temperatures of a final superheater tube situated in both regions, it was developed an algorithm based on empirical correlations to determine the heat transfer coefficients. In the steam flow, the convection heat transfer coefficient is determined by Eq.(1) described in Bazzo (1995). The convection heat transfer coefficient in the combustion gases flow is given by Eq.(2) proposed by Zukauskas (1987 *apud* Bazzo, 1995).

$$h_{internal} = \frac{k_{steam}}{D_{int\,ernal}}\left(0{,}023.Re_{steam}^{\;0{,}8}\,Pr_{steam}^{\;0{,}4}\right) \tag{1}$$

$$h_{external} = \frac{k_{gagses}}{D_{external}}\left(0{,}27.Re_{gases}^{\;0{,}63}\,Pr_{gases}^{\;0{,}36}\right) \tag{2}$$

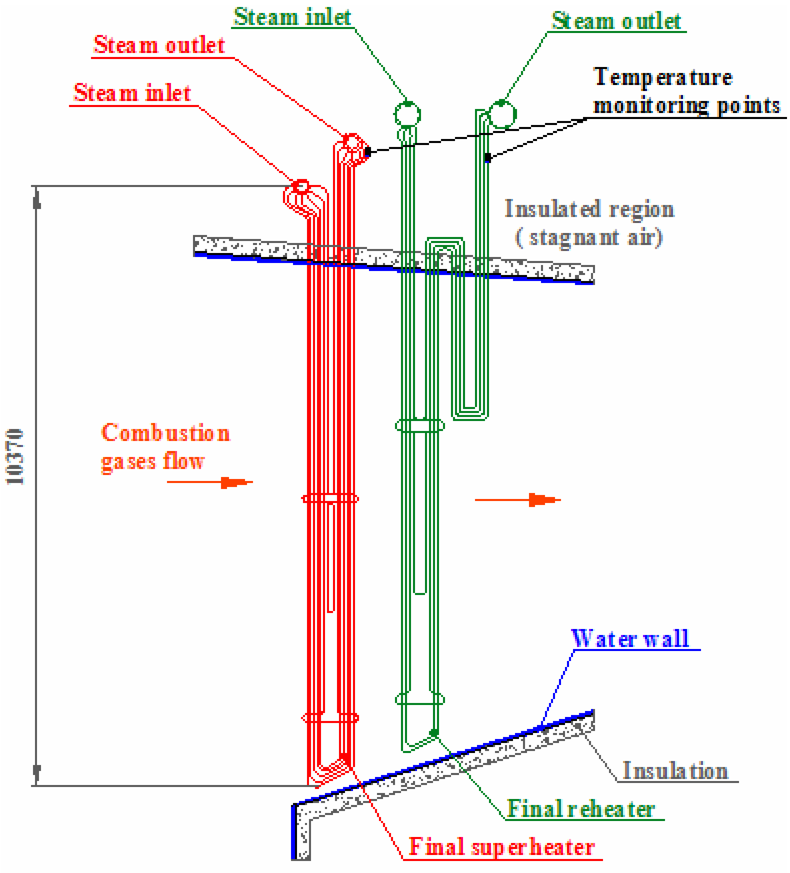


Figure 6 - Scheme of the final superheater and final reheater.

The equivalent heat transfer coefficient by gaseous radiation is determined through Eq.(3) (Bazzo, 1995).

$$h_{radiation} = \frac{\sigma.A.f\left(\varepsilon_{gases}.T_{gases}{}^{4} - \alpha_{gases}.T_{wall}{}^{4}\right)}{\pi.D_{external}.L.\Delta T_{ML}} \quad (3)$$

At the insulated region, the heat transfer coefficient due natural convection is given by Eq.(4) (LeFreve and Ede, 1956).

$$h_{natural\ convection} = \frac{4.k_{air}}{3.H}\left[\frac{7.Ra_{air}.Pr_{air}}{5(20+21.Pr_{air})}\right]^{\frac{1}{4}} + \frac{4.k_{air}(272+315.Pr_{air})}{35.D_{tube}(64+63.Pr_{air})} \quad (4)$$

The results for the unit operating at 125 MW with 2, 3 and 4 burner rows are presented on Figure 7. The temperature difference calculated between the regions varies from 15 °C to 60 °C. The surface temperatures are determined considering the variation of the internal deposed oxide thickness layer. The results show that the monitoring at the stagnant region does not provide realistic values. In this way, the tube surface temperatures should be evaluated at the combustion gases flow region through an apparatus that is able to operate in this aggressive environment.

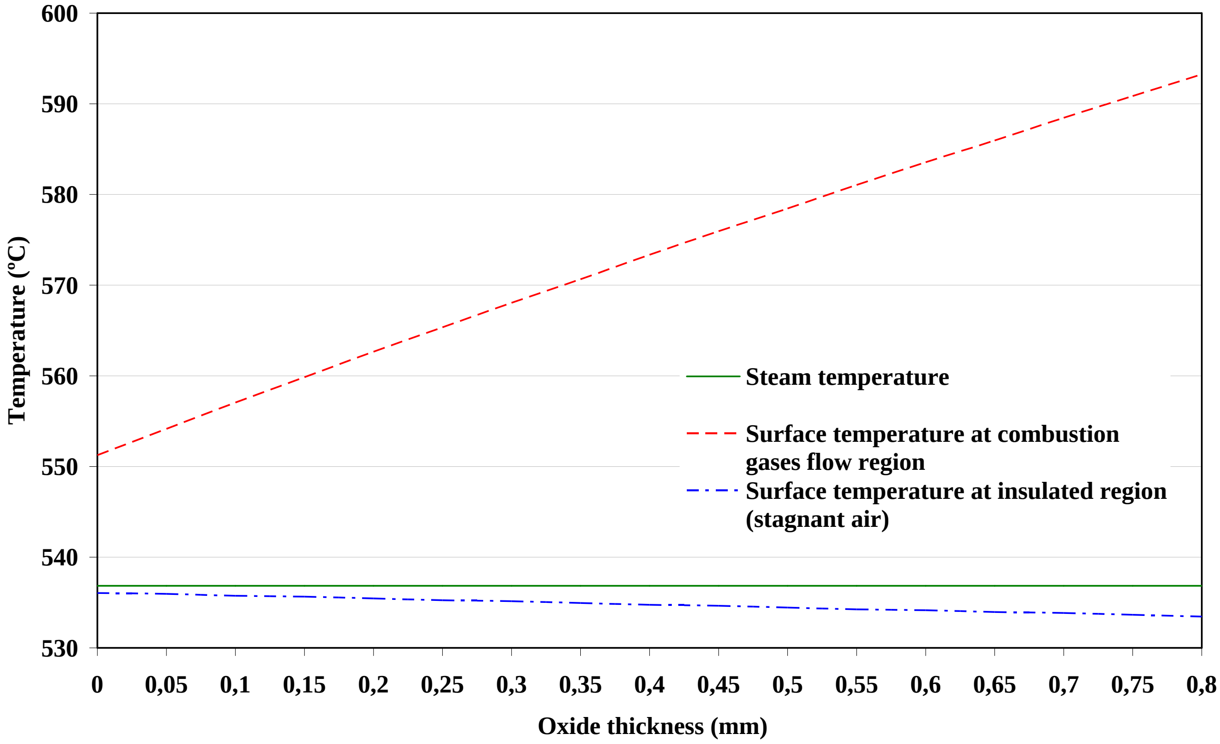


Figure 7 - Surfaces temperatures on the final superheater tube.

5. RESULTS AND DISCUSSION

5.1 Evaluation of different temperature sensors

Experimental results are presented where different testing configurations are compared. The temperatures obtained for an 80 MW power operation using 2, 3 and 4 burner rows are illustrated in Figure 8. The mean temperatures at final superheater given through the shielded sensor and the sensor proposed by ASTM (1974) are 578,1 ^{o}C and 591,3 ^{o}C respectively. At the final reheater the mean temperatures registered through the shielded sensor and the one proposed by ASTM (1974) are 567,2 ^{o}C and 570,4 ^{o}C respectively. It may be observed that temperature differences between the sensors are greater at the final superheater, due to higher temperature of the combustion gases. This shows that a greater amount of heat is absorbed by the metallic sheath of the thermocouple and transmitted to the measurement point.

The surface temperature registered by the shielded sensors are lower than the values obtained with the configuration proposed by ASTM (1974) It shows that the disturbance produced in the temperature field is lower for the shielded sensor. This is a strong evidence that the configuration proposed in this paper provides more realistic results for the surface temperatures of the tubes.

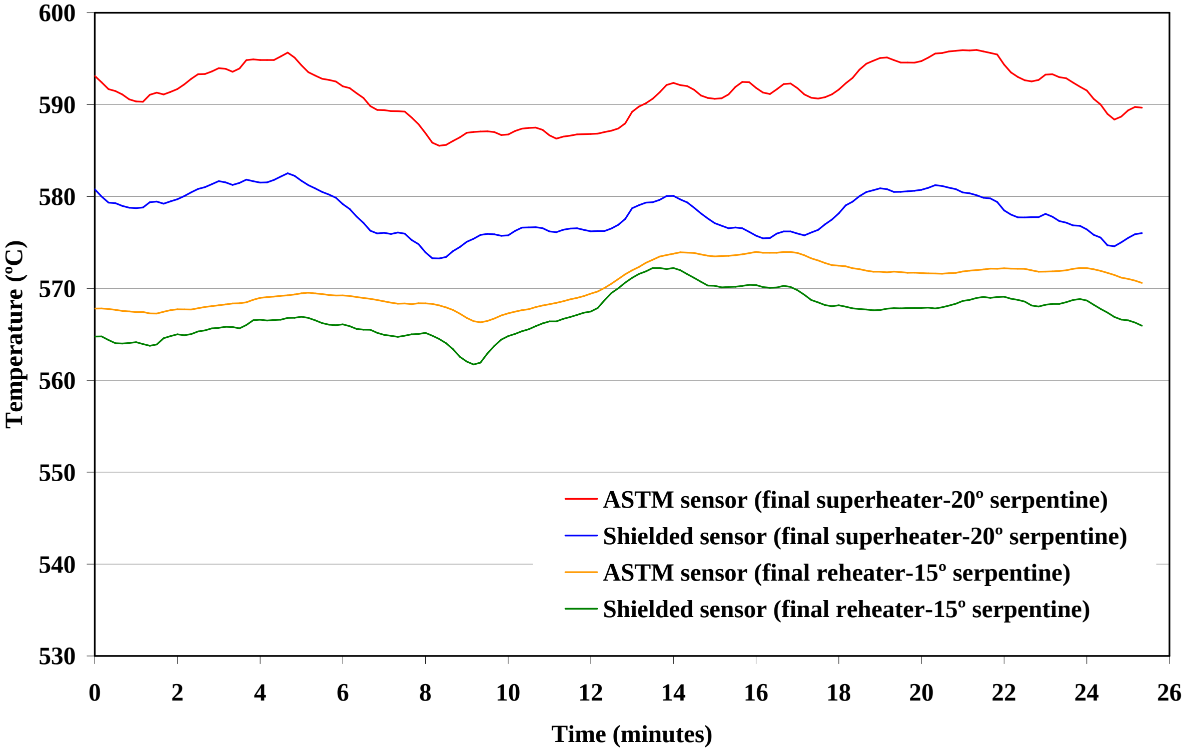


Figure 8 - Surface temperatures measured by the different sensors.

5.2 Surface temperatures of the final superheater and reheater

Surface tube temperatures registered with the shielded sensor were obtained for the following operational conditions:

- 80 MW power operating with 2, 3 and 4 burner rows;
- 110 MW power operating with 1, 2 and 3 burner rows;
- 125 MW power operating with 1, 3 and 4 burner rows.

The mean values obtained for a 30 min time interval are presented in Tab. 2., these preliminary values may justify the high temperatures levels at both tube bundles. The temperatures associated to the 15th serpentine of final reheater were monitored just for 80 MW power operating configuration due a failure of the shielded sensor.

In a general way, all temperatures obtained are above the maximum recommended values (~550 ºC), except for the 38th serpentine of the final reheater. The temperature averages shows strong correlation between final superheater temperatures and operating power. At the final reheater the highest temperatures occur when the 4th burner row is operating; this is due the form-factor between the tube bundles and the flames deriving from burners. It may be observed in Figure 9, that the final superheater can see all burner rows while the final reheater sees the flame radiation only when the 4 burner row operates.

Table 2. Surface Temperatures on Final Superheater and Reheater

	80 MW Burner rows 2, 3, 4	110 MW Burner rows 1,2,3	122 MW Burner rows 1,3,4
Final superheater – 20th serpentine	575,9 ºC	587,9 ºC	596,4 ºC
Final reheater – 15th serpentine	567,2 ºC	-	-
Final reheater – 38th serpentine	545,9 ºC	537,4 ºC	549,2 ºC
Final reheater – 39th serpentine	582,4 ºC	578,9 ºC	597,3 ºC

The temperature difference between 38th and 39th serpentines at final reheater is remarkable, this is due to lower heat exchange area of the 38th serpentine. Actually, some serpentines of the final reheater were reduced to avoid the high temperatures and the results shows that temperatures are 36 to 48 ° C lower throughout these serpentines.

The 15th and 39th serpentines have the same heat exchange area and the results indicate a significant temperature difference, this is due to the position of the serpentines along the boiler. The 39th serpentine is positioned at the central region while the 15th serpentine is in a lateral position close to the water-walls. Several factors contribute to the lower temperatures shown on serpentines closer to the water-walls, among them, the increased steam mass flow and the lower temperature of combustion gases (Silva (2008)).

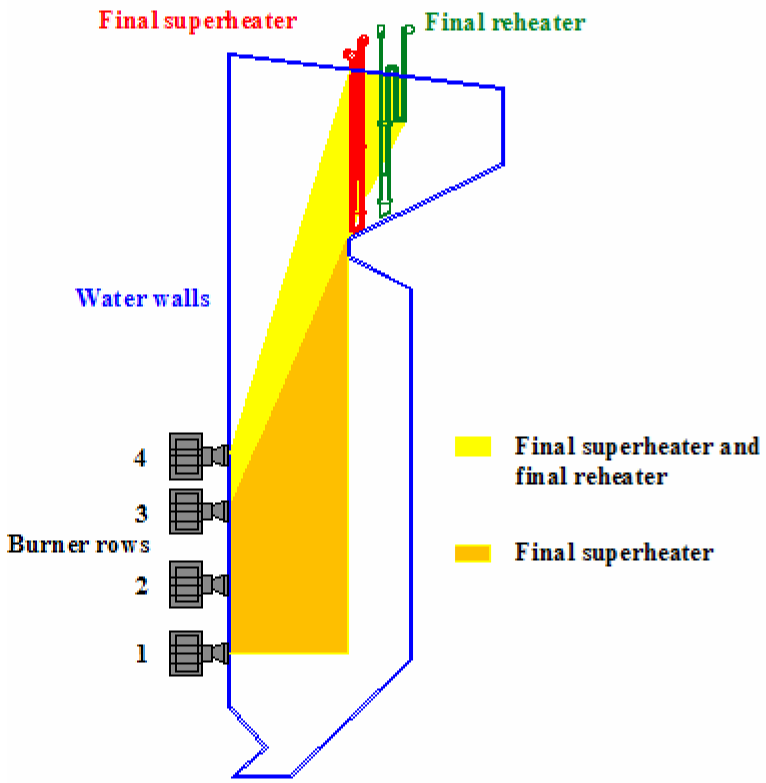


Figure 9 - Position of final superheater and reheater with relation to burner rows.

5.3 Uncertainty of measurement

The different uncertainty sources related to the measurement system were evaluated through the ISO-GUM procedure (Guide to the Expression of Uncertainty in Measurement) and the full analysis is available in Silva (2008). The values of expanded uncertainty obtained in temperature measurements at final superheater and reheater are $\pm 16{,}6\ ^{\circ}\mathrm{C}\,[95{,}45\%;\mathrm{k}=2]$ and $\pm 7{,}5\ ^{\circ}\mathrm{C}\,[95{,}45\%;\mathrm{k}=2]$, respectively. The symbol k is correlated with the coverage factor.

6. CONCLUSIONS

Analysis through empirical correlations indicates that the monitoring of tube wall temperatures should be made at regions with combustion gases flow. Measurement results shows a significant temperature difference between the stagnant air and combustion gases regions (15 to 60 ^{o}C) Additionally, it was observed a strong influence of the mineral oxide thickness on the establishment of surface temperatures.

The mineral insulated thermocouples sensors are better indicated to resist the aggressive environment existing inside boilers, at the same time, provides reliable results since an adequate combination between metallic sheath and thermocouple type is made. The existing methods to attach the measurement junction of a thermocouple on tube surface can lead to inaccurate results. A new configuration was proposed which creates a long path between combustion gases and measuring junction, at the same time, a direct heat path to the tube wall. Experimental results show that the shielded sensor had a better behavior when compared to the usual sensor configuration. The temperature values supplied by the shielded sensor were 13,2 ^{o}C lower than the ones provided by the usual sensors.

Specific tubes of the final superheater and reheater were instrumented with shielded sensors and monitored on different operating conditions. It was then possible identify the factors determining the high temperatures at tube bundles. In the case of the final superheater, the tube temperatures are directly correlated with the operating power, while at the final reheater the tube temperatures depends on the burner rows in operation. The higher tube temperatures were obtained when the 4th burner row was operating. The experimental results show that the serpentines on the final reheater were the ones with less heat exchange and lower surface temperatures as expected. Finally, the positioning of the serpentines in the boiler determines the surface tube temperatures.

7. ACKNOWLEDGEMENTS

The authors would like to thanks the financial support from the Brazilian Electricity Regulatory Agency (ANEEL) for this project. Thanks also to Tractebel Energy, especially to maintenance team of Jorge Lacerda Thermoelectric plant for its assistance during installation of sensors and experimental monitoring. Finally, thanks the CNPq (National Council for Scientific and Technological Development) for its financial support.

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