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THERMAL CHARACTERISATION OF A SOLID WASTE INCINERATOR BY TEMPERATURE MEASUREMENTS WITH SUCTION PYROMETERS

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ABSTRACT

According to the European Waste Directive 2000/76/CE, temperature of gaseous emissions in the postcombustion zone of an incinerator is one of the key parameters that has to be continuously measured and controlled. A bare thermocouple is generally affected by different physical contributes which make the gas temperature measurement incorrect.

This paper analyzes the errors that can arise when using a bare thermocouple, describes principle design and uncertainty of a suction pyrometer and a method to characterize a waste incinerator. Results allow a correct thermal characterization of the plant permitting a better energy management.

INTRODUCTION

The combustion temperature is one of the key parameters that affects the energetic efficiency of incineration plants and also the chemical composition of gaseous emissions[1][2][3].

The European Waste Directive 2000/76/CE sets out operational conditions, technical requirements and emission limit values for incineration and co-incineration plants. As regards to the operating temperature control, the Directive prescribes that:

1. the gas resulting from the process is raised, after the last injection of combustion air, in a controlled and homogeneous fashion and even under the most unfavorable conditions, to a temperature of 850°C, as measured near the inner wall for two seconds. If hazardous wastes with a content of more than 1% of halogenated organic substances, expressed as chlorine, are incinerated, the temperature has to be raised to 1100°C for at least two seconds;
2. the temperature of the gas has to be continuously measured near the inner wall or at another representative point of the combustion chamber;
3. the auxiliary burner, that must equip each line of a incineration plant, must be switched on automatically when the temperature of the combustion gas falls below 850°C or 1100°C as the case may be.

From these brief considerations arises that to respect the EU Directive and also in the study, inspection and conduction of incineration plants is important that measurements of temperature are made with a high degree of accuracy.

NOMENCLATURE

A	[m^2]	Area of a surface available for heat transfer
c	[J/kgK]	Specific heat
d	[m]	diameter
E	[K]	Error of temperature
F	[-]	Radiation form factor
g	[m/s^2]	Gravitational constant
h	[W/m^{2}K]	Heat transfer coefficient
k	[W/mK]	Thermal conductivity
L	[m]	Length
M	[-]	Mach number
Nu	[-]	Nusselt number
$\dot{Q}$	[W]	Heat flux
Re	[-]	Reynolds number
$St.dev.$	[K]	Standard deviation of temperature difference
T	[K]	Temperature
t	[s]	Time
V	[m^3]	Volume
v	[m/s]	Velocity
z	[m]	Distance from a reference line

Special characters

σ	[W/m^{2}K^4]	Stefan-Boltzmann constant
ε	[-]	Emissivity
γ	[-]	Ratio between specific heat at constant pressure and specific heat at constant volume
ρ	[Kg/m^3]	density
τ	[s]	Time constant

Subscripts

cd	Exposed to heat transfer by conduction
cv	Exposed to heat transfer by convection
$cv\text{-}rad$	Exposed to heat transfer by both convection and radiation

e	environment
g	Gas
ind	Indicated
P	At constant pressure
pyr	Pyrometer
rd	Exposed to heat transfer by radiation
ref	Reference
s	Static
st	Stagnation
tc	Thermocouple
tc-wall	From thermocouple to the environmental wall
wall	Wall

ERRORS IN GAS TEMPERATURE MEASUREMENTS

Thermocouples or radiation pyrometers generally used in the almost totality of incinerator plants indicate a temperature that differs, even by many degrees, from the real gas temperature.

In a non adiabatic combustion chamber of a modern radiant-type boiler, the difference between thermocouple and gas temperature in steady –state condition, represents the balancing of four phenomena:

a) heat transfer from the probe to the surroundings by radiation;
b) heat transfer by conduction from the hot junction of the probe to the external surround;
c) heat transfer by convection from gas to the thermocouple;
d) conversion of kinetic energy to thermal energy in the boundary layer to the junction.

During transients, the thermocouple will lag behind any change in gas temperature, due to its thermal capacity, resulting in a response-rate error.

The temperature of the thermocouple junction T_{tc} will stabilize at a level which balances the heat flow by convection between the junction and the gas, against the heat flow by radiation and conduction. The junction temperature can be evaluated by the simultaneous solution of three (four if a transient problem is considered) heat flow rates.

Derivations of the equations for radiant, conductive, convective heat transfer and for response rate are well known [4][5][6]. The following equations are applicable when the environmental effects are small enough so that the presence of one effect does not influence the value of the others. Any difference between thermocouple junction temperature T_{tc} and gas stream total temperature T_g is considered to be an error E.

Conduction error

This error E_{cd} can be calculated considering the thermocouple wire of a length L, immersed in a homogeneous flow at constant temperature T_g and immediately emerging into an environment with temperature T_e.

$$E_{cd} = T_{tc} - T_g = \\ = \frac{T_e - T_g}{\cosh\left[\left(\frac{4h_{cv}}{kd}\right)^{\frac{1}{2}} L\right] + \left(\frac{h_{cv}}{k}\right)^{\frac{3}{2}}\left(\frac{d}{2}\right)^{\frac{1}{2}} \sinh\left[\left(\frac{4h_{cv}}{kd}\right)^{\frac{1}{2}} L\right]} \quad (1)$$

To reduce the error E_{cd} is therefore necessary to immerse the thermocouple in the gas flow with as great a length as possible of small diameter d, with a low thermal conductivity k and increasing the transfer coefficient h_{cv}.

The transfer coefficient h_{cv} between gas and thermocouple can be calculated by the relation between the Nusselt number and the Reynolds number, the following relations [7] are valid for combustion gas where Prandtl number is about 0,7 :

$Nu = (0{,}44 \pm 0{,}06)(\mathrm{Re})^{0{,}5}$ (2) for a thermocouple placed normal to the flow direction, and

$Nu = (0{,}085 \pm 0{,}009)(\mathrm{Re})^{0{,}674}$ (3) for a thermocouple placed along the flow direction.

The gas velocity in a industrial furnace varies, in general between 0 and 80 m/s, as a consequence, h_{cv} is comprised between 0 and 597 W / (m^2 K). These values have been calculated for a type k thermocouple with a diameter of 4 mm and placed normal to the gas flow direction.

Even with temperature differences between gas and environment of more than 800 °C, the error conduction is often negligible if compared with radiation - convection error.

Radiation – convection error

This error $E_{cv\text{-}rd}$ can be calculated considering both the convection and radiation equation (4) and (5):

$$\dot{\mathrm{Q}}_{\mathrm{cv}} = A_{cv}\mathrm{h}_{\mathrm{cv}}(\mathrm{T_g} - \mathrm{T_{tc}}) \quad (4)$$

$$\dot{Q}_{rd} = A_{rd} F_{tc-wall} \sigma\varepsilon(T_{tc}^4 - T_{wall}^4) \quad (5)$$

The radiation – convection error is therefore:

$$E_{cv-rd} = (\mathrm{T_g} - \mathrm{T_{tc}}) = \frac{A_{rd} F_{tc-wall} \sigma\varepsilon(T_{tc}^4 - T_{wall}^4)}{A_{cv}\mathrm{h}_{\mathrm{cv}}} \quad (6)$$

This error for a thermocouple inside an enclosure can be expressed as a simplified form of equation (6), if the enclosure is large compared to the thermocouple diameter. For this case the radiation form factor $F_{tc\text{-}wall}$ equals 1 and the area available for radiation A_{rd} equals the area available for convection A_{cv}, the expression of $E_{cv\text{-}rd}$ can be therefore written as:

$$E_{cv-rd} = (\mathrm{T_g} - \mathrm{T_{tc}}) = \frac{\sigma\varepsilon(T_{tc}^4 - T_{wall}^4)}{\mathrm{h}_{\mathrm{cv}}} \quad (7)$$

To reduce this error, thermocouple emissivity and wall temperature must be maintained as low as possible while h_{cv} must be as high as possible.

Polished metal surfaces have a low emissivity [8] ($\varepsilon \leq 0{,}2$) at temperatures below 250°C but emissivity increases rapidly with temperature as well as by oxidation or deposition on the surface. In some case emissivity of thermocouple can reach 0.8.

The wall temperature can be predicted by the boiler designer as a function of the boiler thermal load and the boiler external conditions. In equations (4-6) the wall temperature should be replaced by the mean radiating temperature of the thermocouple surrounding, the combustion gas is in fact laden with solid particles at temperature and emissivity which are different to that of the gas and the wall too.

Assuming the gas and environmental conditions in a zone of the incinerator plant, the radiation-convection error can be estimated by equation (7). For example, in the post combustion zone, where we can assume that $\varepsilon = 0{,}5$, $T_{tc} = 982{,}33$ °C (see next table 3), h_{cv} =350 W / (m^2 K) and T_{wall} = 600 °C, the error $E_{cv\text{-}rd}$ is therefore equal to 153,88 °C.

Velocity error

The energy conservation balance for a open system in a steady state condition, for a one-dimensional flow in an adiabatic process allows to calculate the temperature of the gas:

$$T_g = T_s + \frac{v^2}{2c_P} + \frac{gz}{c_P} = T_{st} + \frac{gz}{c_P} \cong T_{st} \quad (8)$$

Where T_s is the static gas temperature. Under these hypothesis, when the potential energy term is negligible, the total gas temperature T_g equals the stagnation temperature T_{st}, i.e. the temperature which the gas would attain if brought to rest adiabatically against the thermocouple.

When the gas velocity is high, a considerable part of its total energy is in the form of directed kinetic energy. Not all of this is converted to thermal energy in the boundary layer[9] around the thermocouple junction, a part of this energy is dissipated by conduction through the fluid. For this reason the temperature of the thermocouple surface differs from the stagnation temperature, so that the velocity error for incompressible flow is:

$$E_v = T_g - T_{tc} = (1-\alpha)\frac{v^2}{2c_P} \quad \text{if } M < 0{,}25 \quad (9)$$

For one-dimensional isentropic compressible flow the error velocity can be written as:

$$E_v = T_g - T_{tc} = (1-\alpha)\frac{[(\gamma-1)/2]M^2}{1+[(\gamma-1)/2]M^2} \quad \text{if } 0{,}25 < M < 3 \quad (10)$$

M is the Mach number, c_P is the specific heat of the gas at constant pressure, γ is the ratio of specific heats and α is the kinetic energy recovered by the boundary layer, this one is defined as:

$$\alpha = \frac{T_{tc} - T_s}{T_g - T_s} \quad (11)$$

Values of α available in the literature [7] are:

α = 0,68 ± 0,07 for a thermocouple placed normal to the flow direction, and

α = 0,86 ± 0,09 for a thermocouple placed along the flow direction.

Transient error

The temperature of a thermocouple junction will always lag behind any change in the temperature of the gas in which it is immersed. Heat must be transferred between the gas and the junction to accomplish a change in junction temperature. The rate of heat transfer depends on the values of h_{cv}, of the area available for convection and on the difference between junction and gas temperature. Such a temperature difference must then exist if the junction temperature is changing with time. Its magnitude E_t can be calculated from the measured rate of change of junction temperature, as shown in equation (12):

$$E_t = T_g - T_{tc} = \tau\frac{\partial T_{tc}}{\partial t} \quad (12)$$

The behaviour of a thermocouple during a transient can be expressed in terms of its time constant, defined in equation (13):

$$\tau = \frac{\rho c V}{h_{cv} A_{cv}} \quad (13)$$

Where ρ, c and V are respectively the density, the specific heat and the volume of the thermocouple junction.

Bare thermocouples placed in the post-combustion-zone of an incinerator plant are particularly subject to structural alterations by chemical corrosion, oxidation and fuse salts deposition. Consequently their constant time can vary by many orders during measurement time.

The equations presented in this section reveal the reason why the calculated error for a bare junction is so sensitive to the accuracy of the estimate of the environmental conditions.

INCINERATOR STRUCTURE

In a line of a radiant type boiler of a modern incinerator plant (figure 1), where gas velocity varies between 10 and 80 m/s, the radiation - convection error is the greatest one, this is specially true in the post - combustion and radiant zones where gas temperatures are higher. For the post-combustion zone the EU Directive imposes that gas temperature has to be maintained at least 850°C. For this reason and to avoid methane consumption by auxiliary burners, the temperature measurement has to be performed with acceptable accuracy.

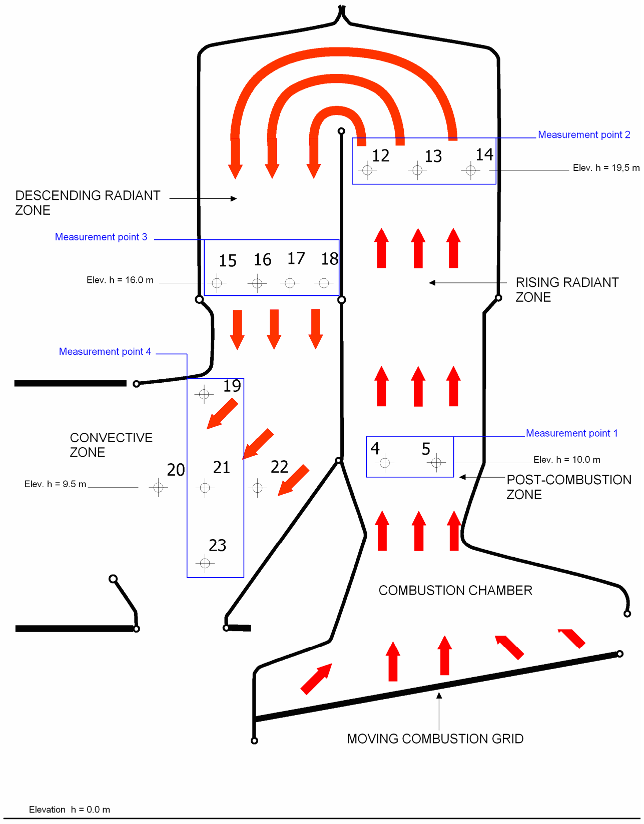

Figure 1 Shape of the radiant type boiler of a modern incinerator with the indication of measurement points.

SUCTION PYROMETERS

In order to minimize the errors discussed in the previous section and to obtain the thermal characterization of an incinerator plant, it is possible to perform the temperature measurement with six pyrometers simultaneously.

Each pyrometer [10] consists of a thermocouple protected from chemical action of the gas by an impermeable titanium sheath and placed in a system of low emissivity ceramic shields that isolate the thermocouple from the surrounding radiation. The titanium sheath is cooled by circulation of a water flow; for a water temperature of 20°C the flow rate has to be at least of $0.34 \cdot 10^{-3}$ m^3/s.

The gas is sucked at high velocity through the screens and over the sheath by a compressed air ejector. The gas velocity varies between 100 and 200 m/s.

In figure 2 a suction pyrometer is placed in a combustion chamber, normally to the gas direction. In the same figure a link between pyrometer, cooling and air compressed systems can be distinguished and also the connection between thermocouple and data acquisition system.

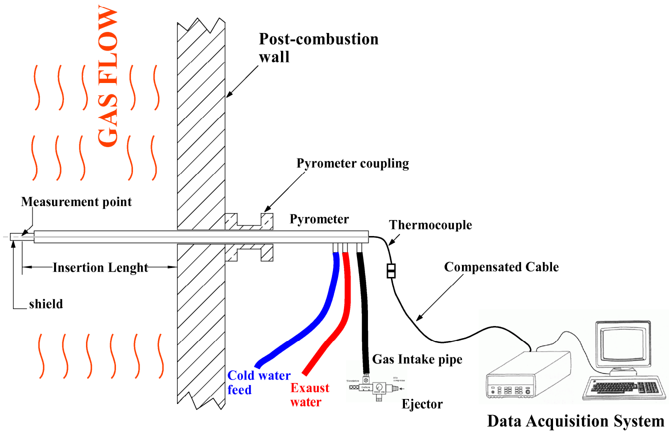

Figure 2 Lay out of a suction pyrometer with ancillary and data acquisition systems.

In our measurements we may use six suction pyrometers, three of them have a nominal length of four meters, one of these is equipped with a type s (Pt-10%Rh/Pt) thermocouple and the other two with a type k (Ni-Cr/Ni-Al) thermocouple. The other three pyrometers have a nominal length of two meters, one of these is equipped with a type s thermocouple and the other two with a type k thermocouple. Suction pyrometers equipped with a type k thermocouple can perform measures up to 1200°C while ones equipped with type s thermocouple can perform temperature measures up to 1600°C.

Every thermocouple has been calibrated in a S.I.T. (Italian Calibration Service) Laboratory, in the next tables 1 and 2 are reported the measurement chain calibrations. The measurement chain is composed by thermocouple, compensated cable and data acquisition system.

Table 1 Calibration results for a type k thermocouple.

Point n°	Reference temperature T_{ref} [°C]	Indicated temperature T_{ind} [°C]	T_{ref}-T_{ind} [°C]	Expanded uncertainty [°C]
1	752.68	750.7	-1.98	1.41
2	853.89	852.5	-1.39	1.41
3	954.88	954.2	-0.68	1.41
4	1056.96	1056.5	-0.46	1.40

Traceability of calibration results to the international standards of the International System of Units (SI). The measurement uncertainties have been estimated as expanded uncertainty obtained multiplying the standard uncertainty by the coverage factor corresponding to a confidence level of about 95%.

Table 2 Calibration results for a type s thermocouple.

Point n°	Reference temperature T_{ref} [°C]	Indicated temperature T_{ind} [°C]	T_{ref}-T_{ind} [°C]	Expanded uncertainty [°C]
1	752.68	751.80	-0.88	1.01
2	853.89	853.00	-0.89	1.01
3	954.88	954.20	-0.68	1.01
4	1056.96	1056.70	-0.26	1.01

TEMPERATURE MEASUREMENT RESULTS

In this work temperature measurements have been performed using from one to three pyrometers at the same time, in figure 1 are indicated the measurement points, where the pyrometers have been introduced in the incinerator boiler. A multiple pyrometer insertion (figure 3), combined with a variable insertion length, allows to estimate the temperature profile in some characteristic zone of the incinerator plant.

Figure 3 Three suction pyrometers inserted at the top of the rising radiant zone.

The heating load of the plant has been maintained as much as possible constant during all measurement operations. In an incinerator plant a steady state condition is not so easy to be maintained, the solid waste heat value depends in fact on its mass composition and varies from 9200 and 13800 kJ / kg, with a typical mean value of 10800 kJ / kg. The plant monitored during this work is designed for a heating load that varies from a minimum of 26 tons of steam per hour to a maximum of 40 tons of steam per hour, the nominal load is 33 tons per hour.

Temperature data shown in the next tables have been measured with the plant at its nominal heating load. Measurements at the minimum load have been performed too, and the behaviour of thermocouple and pyrometers in this condition is the same even if temperatures are lower.

The data acquisition system has been set with a sampling frequency of 1 Hz, every temperature measure has been performed for at least one hour with the incinerator plant at the same heating load.

Temperature measurement in the post combustion zone has been performed with one suction pyrometer inserted in borehole 4 of the measurement point 1 (figure 1), a bare thermocouple has been inserted in the borehole 5 of the same measurement point. This thermocouple is used to control the automatic switch of auxiliary burners when the temperature falls below 850°C. Both the pyrometer and the thermocouple have been inserted near the inner wall of the incinerator.

Results of temperature measurement in the post combustion zone are reported in the next table 3. $\overline{T}_{pyr}$ and $\overline{T}_{tc}$ are the mean of temperature measured respectively by the pyrometer and the bare thermocouple. $\overline{T_{pyr}-T_{tc}}$ is the mean of the temperature difference between pyrometer and thermocouple and St.dev. is the standard deviation of the temperature difference.

Table 3 Mean temperature values in the post combustion zone.

$\overline{T}_{pyr}$ [°C]	$\overline{T}_{tc}$ [°C]	$\overline{T_{pyr}-T_{tc}}$ [°C]	St.dev. [°C]
1130.59	982.33	148.27	32.59

$\overline{T_{pyr}-T_{tc}}$ in table 3 is consistent with the radiation-convection error estimated before with equation (7).

Temperature measurement in the rising radiant zone have been done using three pyrometers at the top of it, in the measurement point two (figure 1). A bare thermocouple has been placed near the inner wall at the opposite side of borehole 12. Temperature data and comparison between pyrometer in borehole 12 and the thermocouple at the opposite side are reported in table 4.

Table 4 Mean temperature values in the rising radiant zone, pyrometer in borehole 12 and bare thermocouple at opposite side.

$\overline{T}_{pyr}$ [°C]	$\overline{T}_{tc}$ [°C]	$\overline{T_{pyr}-T_{tc}}$ [°C]	St.dev. [°C]
835.87	726.61	121.26	18.82

In table 5 are reported the mean temperature values measured by pyrometers placed in boreholes 12, 13 and 14, as a function of the distance from the inner wall.

Table 5 Mean temperature values in the rising radiant zone.

Insertion length [mm]	Borehole 12 $\overline{T}_{pyr}$ [°C]	Borehole 13 $\overline{T}_{pyr}$ [°C]	Borehole 14 $\overline{T}_{pyr}$ [°C]
0	835.21	852.63	831.64
100	862.65	873.86	843.98
200	908.67	921.92	871.51
1500	n.a.[1]	933.39	927.83

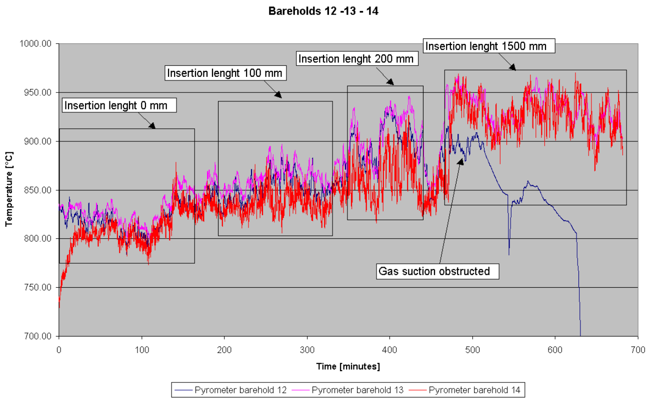

Figure 4 Temperature measurements in the rising radiant zone.

Temperature measurements in the descending radiant zone have been done using three pyrometers in the boreholes 15, 16 and 18, in the measurement point three (figure 1). A bare thermocouple has been placed near the inner wall in borehole 17. Temperature data and confrontation between pyrometer in borehole 16 and the thermocouple in borehole 17 are reported in table 6.

Table 6 Mean temperature values in the descending radiant zone, pyrometer in borehole 16 and bare thermocouple in borehole 17.

$\overline{T}_{pyr}$ [°C]	$\overline{T}_{tc}$ [°C]	$\overline{T_{pyr}-T_{tc}}$ [°C]	St.dev. [°C]
737.01	686.20	50.91	8.34

In table 7 are reported the mean values of temperature measured by pyrometers placed in boreholes 15, 16 and 18, as a function of the distance from the inner wall.

Table 7 Mean temperature values in the descending radiant zone, borehole 15, 16 and 18.

Insertion length [mm]	Borehole 15 $\overline{T}_{pyr}$ [°C]	Borehole 16 $\overline{T}_{pyr}$ [°C]	Borehole 18 $\overline{T}_{pyr}$ [°C]
0	715.32	737.02	726.89
100	718.74	738.25	729.07
200	722.51	740.35	730.9
1500	740.00	759.42	748.86

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[1] The suction pyrometer has been obstructed by accumulation of scraps.

Table 8 Mean temperature values in the convective zone, borehole 19, 21 and 23.

Insertion length [mm]	Borehole 19 $\bar{T}_{pyr}$ [°C]	Borehole 21 $\bar{T}_{pyr}$ [°C]	Borehole 23 $\bar{T}_{pyr}$ [°C]
100	693.95	654.37	642.11
300	690.82	672.73	671.22
1500	755.27	720.09	688.93

Temperature measurements at the beginning of the convective zone have been performed using three pyrometers in the boreholes 19, 21 and 23, in the measurement point four (figure 1). Results of temperature measurements in this zone are reported in table 8.

The error arising with a bare thermocouple can be estimated, in precautionary manner, as the difference between the mean of the temperature difference between pyrometer and thermocouple $\overline{T_{pyr} - T_{tc}}$ and its standard deviation. This error is a function of the gas temperature and confirms that the convection – radiation error is the most significant one.

The calibration uncertainty is negligible compared with the influence of physical effects.

In table 9 are summarized the estimated errors of the bare thermocouples used in this study, as a function of the incinerator plant zone.

Table 9 estimated errors arising with a bare thermocouple.

Incinerator zone	$\overline{T_{pyr} - T_{tc}}$ [°C]	St. Dev. [°C]	Estimated bare thermocouple error [°C]
Post combustion	148.27	32.39	115.88
Rising radiant	121.26	18.82	90.44
Descending radiant	50.91	8.34	42.47

CONCLUSION

This work demonstrates that temperature measurements with suction pyrometers may result more accurate than that obtained with a bare thermocouple. The measured temperature differences depend mainly to the temperature of the surrounding and may results more than 100°C.

In the examined incinerator plant all the temperatures measured with suction pyrometers are effectively higher than that obtained by bare thermocouples. The temperature measured in the post combustion zone by the suction pyrometer has been used to correct the bare thermocouple reading in the same zone. This correction has permitted a considerable reduction of the auxiliary burners switch on time, as a consequence the methane consumption has been reduced of more than 50%.

These results permits to affirm that utilization of suction pyrometers in an incinerator plant, allows the calibration of the bare thermocople used by the plant conductor to control the operating temperature of the plant and permits a better energy management of the plant. The bare thermocouple calibration has to be made in a condition as near as possible to the steady state and is valid only for the heating load and for the measurement point used during the measurement process.

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