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Energy Procedia 120 (2017) 317–324

Energy Procedia

www.elsevier.com/locate/procedia

INFUB - 11th European Conference on Industrial Furnaces and Boilers, INFUB-11

An optimal algorithm to assess the compliance with the T_{2s} requirement of Waste-to-Energy facilities

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Abstract

The gas resulting from the incineration of waste must be 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 at least 850 °C for at least two seconds (Art. 50.2 Directive 2010/75/EU). This norm and its variations (i.e. 1,100 °C for 2 s if the chlorine content of the incinerated waste exceeds 1% by mass), called "T_{2s} requirement", oblige all Waste-to-Energy (WtE) plant operators to monitor the post-combustion conditions and to turn on auxiliary burners in the occurrence of noncompliance with such a requirement. In a WtE boiler, the determination of the mean temperature reached by combustion gas in the post-combustion zone, after an ideal residence time of 2 s, is carried out by an algorithm implemented in the Distributed Control System (DCS) of the plant. Currently, since many different algorithms are used, it appears that further investigation on this subject is required.

This work considers, as a case study, an existing WtE boiler and, by means of a calibrated long-furnace model of the post-combustion zone, investigates all the possible operating conditions as well as their connections with the monitored variables. The most relevant influences on the T_{2s} temperature are highlighted and some control algorithms are proposed.

The results so far obtained show that the T_{2s} is affected both by boiler load and gas-side fouling in the same way and for the same extent. Therefore, since gas-side fouling in the post-combustion zone is an uncontrollable variable, boiler load is not usable in as input variable of a reliable algorithm. Moreover, the results highlight the significant role that can be played in the algorithm for the estimation of the T_{2s} by the oxygen content in secondary flue gas.

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Peer-review under responsibility of the organizing committee of INFUB-11

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Peer-review under responsibility of the organizing committee of INFUB-11
10.1016/j.egypro.2017.07.225

Keywords: Waste-to-Energy; T_{2s} requirement; temperature after two seconds; suction pyrometer; boiler model; control algorithm.

1. Introduction

The gas resulting from the incineration of waste must be 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 at least 850 °C for at least two seconds [1]. This norm and its variations (i.e. 1,100 °C for 2 s if the chlorine content of the incinerated waste exceeds 1% by mass), called "T_{2s} requirement", oblige all Waste-to-Energy (WtE) plant operators to monitor the post-combustion conditions and to turn on auxiliary burners in the occurrence of noncompliance with such a requirement. In a WtE boiler, the determination of the mean temperature reached by combustion gas in the post-combustion zone, after an ideal residence time of 2 s, is carried out by an algorithm implemented in the Distributed Control System (DCS) of the plant. Currently, no standard algorithm structure exists. A survey of the used methods was carried out and showed that different variables are measured and used for the estimation of the T_{2s} temperature, as well as algorithm parameters vary from plant to plant and even among the identical incineration lines of the same WtE plant. Table 1 summarizes the variables used by the algorithms adopted in five WtE plants.

Table 1. Variables used by the algorithms adopted in five WtE plants.

	Plant 1	**Plant 2**	**Plant 3**	**Plant 4**	**Plant 5**
Measured temperatures	X	X	X	X	X
Boiler load	X	X		X	X
Flue gas flowrate at stack			X		
Concentration of oxygen in flue gas				X	X

The T_{2s} temperature is normally estimated by means of such a sort of algorithm, which is typically calibrated by means of experimental procedures (like the one adopted in Germany [2]), based on the measurement of temperature in the post-combustion zone with suction pyrometers. However, the measurements cannot be presumed to be representative of any working condition of the boiler, since they are normally carried out in a limited set of conditions. The only operating parameter whose influence is explicitly investigated during the measurements is usually the boiler load (i.e. the steam production).

The T_{2s} temperature primarily depends on the mean temperature of flue gas in the post-combustion zone and on the flowrate of such gas. More schematically, it can be related to the flue gas flowrate and to its temperature at the entrance of the post-combustion zone. However, both these data are not easily retrievable: the flowrate is usually measured only at the stack of the plant, with some minutes of delay and after the unmeasured dilution operated by the ambient air introduced along the gas path; the temperature can be measured with a reasonable accuracy only by means of laboratory instruments, like suction pyrometers, and for limited time.

To warrant the compliance with the norm, during WtE plant operation, the T_{2s} temperature must be estimated with a sufficient safety margin based on easily available data, like the boiler load, the concentration of oxygen, measured temperatures, etc. The preference of most operators is to limit as much as possible the number of variables involved, by considering only those directly measured on the boiler, rather than those measured on other plant sections (like the flue gas flowrate, normally measured only at the stack).

The aim of this work is to investigate the dependence of the T_{2s} temperature of a WtE boiler from controllable (e.g. boiler load, oxygen concentration) and exogenous (e.g. LHV of the burned waste, boiler fouling) variables, to define possible algorithms that, based on few easily available operating data, can estimate with sufficient reliability the T_{2s} temperature. The sought result, considering also the effect of the exogenous factors, should always be a conservative estimate of the actual T_{2s}, featuring a sufficient safety margin with respect to the normative requirement.

2. Case study

The boiler of an existing WtE plant, on which some measurements have been recently carried out, has been considered as a case study for this work. This allowed calibrating all the parameters of the model later described against real data. The calibration concerned the heat loss coefficient, geometrical factors of the combustion chamber, fouling coefficients for the gas-side of the boiler.

The considered plant features three large incineration lines with water-cooled grate combustors, dual stage combustion, pre-heated primary combustion air, semi-dry flue gas treatment system. It is fed only with pre-treated municipal solid waste and was originally designed for RDF (Refuse Derived Fuel) processing.

3. Boiler model

The simulation of flue gas cooling along the post-combustion zone of a WtE boiler requires several models:

- a waste model, in terms of chemical composition and energy content; it allows determining the air requirement, the flue gas production and the energy release during combustion;
- an overall lumped model of the boiler, in terms of overall mass and energy balances; this model basically sets the connection between waste throughput and steam production;
- a model of the primary combustion zone, immediately above the grate; it is needed to determine the amount, composition and temperature of the flue gas produced in such a zone, as well as the thermal power exchanged with the combustion chamber walls;
- a model of the secondary combustion zone, which allows calculating the final composition of flue gas, as well as their temperature after mixing and reacting with the secondary combustion air;
- a model of the post-combustion zone; it is needed to evaluate flue gas and walls mean temperatures along the gas path.

The thermo-chemical properties of flue gas have been calculated by means of NASA polynomials [3], whereas its emissivity has been calculated according to the Leckner's method [4]. The corresponding gas absorptivity has been calculated by means of the Hottel's rule [5]. Finally, the effects of the typical high fly ash load in flue gas has been considered adopting the approach proposed in the VDI Heat Atlas [6].

3.1. Waste model

The waste model has been adopted from Fellner et al. [7]. Their work showed that, for the purpose of mass and energy balances, waste can be considered as composed of four components:

- ash, that is the dry inorganic part of the waste, which can be considered inert during combustion;
- moisture, that behaves as liquid water, absorbing its latent heat of evaporation during combustion;
- dry biogenic matter, i.e. the combustible fraction of biogenic origin – it features a limited LHV and as much limited consumption of oxygen and production of flue gas per unit mass during combustion;
- dry fossil matter, that is the combustible fraction of fossil origin – it comprises mainly plastic materials, which feature rather relevant LHV and as much relevant consumption of oxygen and production of flue gas per unit mass during combustion.

Since each component features a certain LHV, as well as specific consumption of oxygen and production of flue gas, practically any waste can be modelled by changing the shares of the four components. Table 2 summarizes the specific properties adopted in this work for these four waste components.

Table 2. Properties of ash, moisture, dry biogenic matter and dry fossil matter adopted in this work.

	Ash	**Moisture**	**Dry biogenic matter**	**Dry fossil matter**
LHV, MJ/kg	0.0	-2.4425	18.5	36.0
Stoichiometric consumption of oxygen, Nm^3/kg	-	-	0.9294	2.0485
Stoichiometric production of dry flue gas, Nm^3/kg	-	-	4.3846	9.2304
Stoichiometric production of water vapour, Nm^3/kg	-	-	0.7323	1.2173

3.2. Overall lumped model of the boiler

Fig. 1 depicts the scheme of the considered boiler enclosed in a control volume. The model entails the mass, elemental and energy balances of the gas-side of the boiler, as well as the mass and energy balances of the water/steam-side.

The mass and elemental balances of the gas-side connect the flowrates and compositions of the entering streams (e.g. combustion air, waste) to the flowrates and compositions of the exiting streams (e.g. flue gas, bottom and fly ashes). The energy balance of the same side gives the gross heat exchanged in the boiler.

Whilst the mass balance of the water/steam-side of the boiler is a simple relation between feedwater flowrate and steam production (possibly accounting for the continuous blow down and other steam extractions), the energy balance of this side gives the steam production, once steam parameters and feedwater conditions are set. The connection between the energy balances of the two boiler sides is the gross heat exchanged, which determines the steam production after the cutback due to boiler convection and radiation losses.

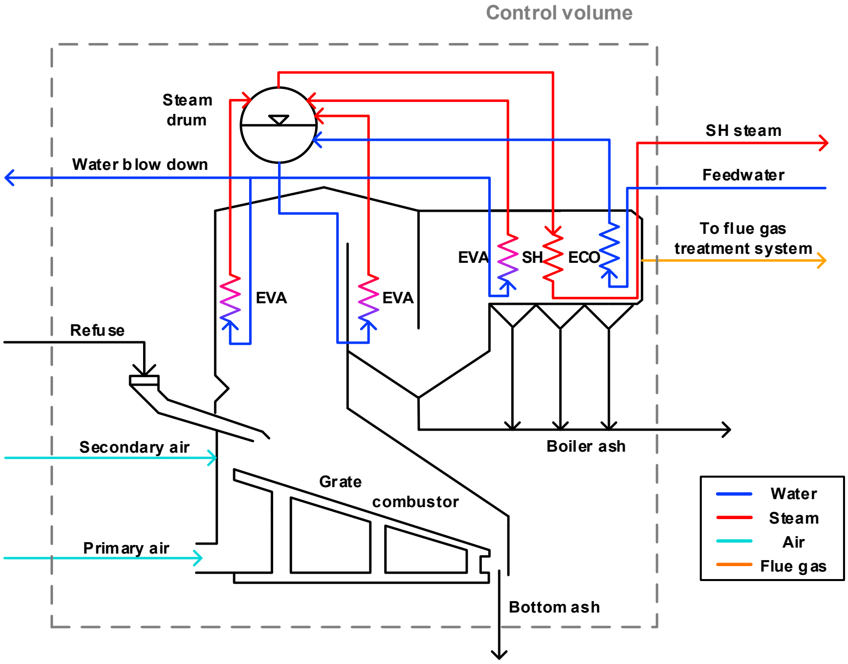

Fig. 1. Scheme of the considered boiler, enclosed in a control volume.

3.3. Primary combustion model

Primary combustion takes place over the grate in conditions that can be, and usually are, sub-stoichiometric. Therefore, significant amounts of gaseous species of incomplete combustion are produced. By adopting the simplest two-step model of combustion [8], the only gaseous species of incomplete combustion considered is carbon monoxide (CO). From the point of view of mass and elemental balances, the model is based on the application of stoichiometry. Concerning the energy balance, instead, the Gurvich's model for combustion chambers [9] has been adopted. This approach condenses all the data describing geometry, flowrates and properties into few characteristic coefficients, to allow calculating the ratio between the actual temperature of flue gas at the exit of the chamber and its corresponding adiabatic temperature, hence the heat exchanged in the chamber. Other authors [10] have already used such a model for WtE boilers. In this case, the only adaptation with respect to the original version of the model lies in the expression of the energy theoretically released during primary combustion. Since primary combustion can be sub-stoichiometric, the heat release can be less than the LHV of the burned waste.

3.4. Secondary combustion model

Secondary combustion takes place at a certain height above the grate, where secondary combustion air is introduced. To properly consider this phenomenon from the standpoint of mass and elemental balances, again stoichiometry is applied, by assuming complete oxidation of all the gaseous species. The secondary combustion zone corresponds to the first cell in the computation scheme use to model the post-combustion zone, as described in the following. Therefore, its energy balance is solved according to such a scheme.

3.5. Post-combustion zone model

Since the crucial point in evaluating the behavior of the T_{2s} is what happens in the post-combustion zone, its model is the most sophisticated among those here discussed. It entails a 1-D scheme along the gas path, according to the long-furnace approach proposed by Herapath and Peskett [11]. The peculiarity of this scheme is the explicitly considered radiant heat exchange among consecutive gas elements. This is done by means of imaginary, transparent and diffusive surfaces. The approach allows a fine discretization of the gas path, thanks to the consistency of the method with regard to the length of the gas elements.

Special attention has been devoted to coupling this scheme with the Gurvich's model for the combustion chamber. The net radiation predicted by the latter on the imaginary surface dividing the combustion chamber from the post-combustion zone has been matched with the difference between radiosity and irradiance of the same surface on the post-combustion side.

By drawing the energy balance of each gas element in terms of absolute enthalpies, also the thermal effects of chemical reactions have been considered. This is particularly true for the first cell of the post-combustion zone, where secondary combustion takes place.

4. Investigated operating conditions

Since the operator of a WtE plant has many degrees of freedom in controlling the combustion process, and many exogenous factors can influence it, a throughout survey of all the independent variables has been carried out. The influence of ambient conditions and the degree of preheating of combustion air has been considered by means of four possible sets of values, summarized in Table 3.

Table 3. Sets of values considered for ambient conditions and combustion air preheating.

	Set 1	**Set 2**	**Set 3**	**Set 4**
Ambient temperature, °C	0.0	0.0	40.0	40.0
Ambient humidity, $g/kg_{\text{dry air}}$	2.0	2.0	25.0	25.0
Primary air temperature, °C	5.0	120.0	45.0	120.0
Secondary air temperature, °C	5.0	5.0	45.0	45.0

For those input variables showing appreciable influence on the T_{2s}, several values have been tested, whereas those less influent have been set to values representative of normal operation. Table 4 lists all the considered variables with the corresponding values so far tested: all their combinations have been used as simulation inputs in each of the four sets of assumptions regarding ambient conditions and combustion air preheating. The total number of possible combinations is almost 18,000, however, not all of them are feasible: as an example, the highest LHV value is not compatible with the highest value of moisture content. The feasible simulations resulted circa 15,000.

Table 4. Operating variables that influence the T_{2s} and their values used to carry out the simulations.

Input variable	# of values	Considered values
Boiler load (i.e. steam production), t/h	5	88.55 – 98.04 – 107.53 – 114.31 – 117.01
LHV of waste, MJ/kg	3	10 – 15 – 20
Moisture content of waste, %	3	15 – 30 – 35
Ash in the waste, kg/kg_{dry}	1	0.18
Lambda factor of primary combustion	3	0.8 – 0.9 – 1
Grate cooling power, MW	1	1.7
Oxygen in the secondary flue gas, $\%_{Vol.}$	11	4.5 – 4.7 – 5 – 5.3 – 5.5 – 5.7 – 6 – 6.3 – 6.5 – 6.7 – 7
Fouling coefficient for the gas-side of the boiler, m^2K/W	3	0.008 – 0.013 – 0.02
Flue gas temperature at boiler outlet, °C	1	175
Discharge temperature of bottom ash, °C	1	450
Mean discharge temperature of fly ash, °C	1	400
Unburnt carbon in bottom ash, kg/kg_{dry}	1	0.01
Unburnt carbon in fly ash, kg/kg_{dry}	1	0.03
Waste ash to bottom ash, %	1	90.0
Fly ash at the exit of the boiler / Total fly ash, %	1	66.7
Fouling factor in the Gurvich's model	1	0.2
Total number of combinations	4,455 x 4	

5. Results and discussion

The first outcome of our analysis concern the relation among simulation results and the temperature measured in the post-combustion zone of the boilers by the plant instrumentation. Such a temperature is the main input variable for the T_{2s} estimation algorithm. In the case study, it is denoted as T_{24m}, since it is measured at the plant elevation of 24 m. Given that flue gas temperature is higher than that of the internal surface of the boiler walls, the measured temperature is somehow half way between these two temperatures.

The simulation of the 18 cases for which experimental data are available not only allowed calibrating the boiler model, but also gave the possibility of comparing the measured T_{24m} with the temperatures estimated by the model at 24 m elevation for flue gas and for the internal surface of boiler walls. The best fitting of the experimental data is obtained when the measured temperature is represented by a weighted average of the two temperatures given by the model. The two weights are 18% for the flue gas temperature and 82% for the temperature of the internal surface of the boiler walls. The graph in Fig. 2 shows the comparison between measured (blue) and estimated (orange) T_{24m} for all the cases: the estimated temperature resulted meanly 0.5 °C lower than the measured one, with a standard deviation of circa 36 °C.

In the considered plant, flue gas temperature is measured at a certain distance from the last injection of combustion air (i.e. the secondary air), corresponding to the plant elevation of 24 m. Such a position was probably chosen by the boiler manufacturer to be as close as possible to the average position where the plane of 2 s ideal residence time is found. However, even in the case the temperature is measured in a different location of the post-combustion zone, the same procedure adopted for the T_{24m} can be applied.

Once the measured temperature (i.e. the T_{24m} in our case) can be estimated for each simulation, the resulting T_{2s} can be plotted against this variable. The graphs in Fig. 3 show the results, colored as functions of steam production in plot (a), and of gas-side fouling coefficient in plot (b). The T_{2s} is affected both by boiler load and gas-side fouling in the same way and for the same extent. Consequently, since gas-side fouling in the post-combustion zone is an uncontrollable variable, boiler load is not usable as input variable in a reliable algorithm.

The simplest algorithm to estimate the T_{2s} as a function of T_{24m} is the minimum envelope of the cloud of points in the two graphs in Fig. 3. Therefore, a linear function is obtained:

$$T_{2s}\left[°C\right] = 0.4247 \cdot T_{24m}\left[°C\right] - 578.9 \qquad (1)$$

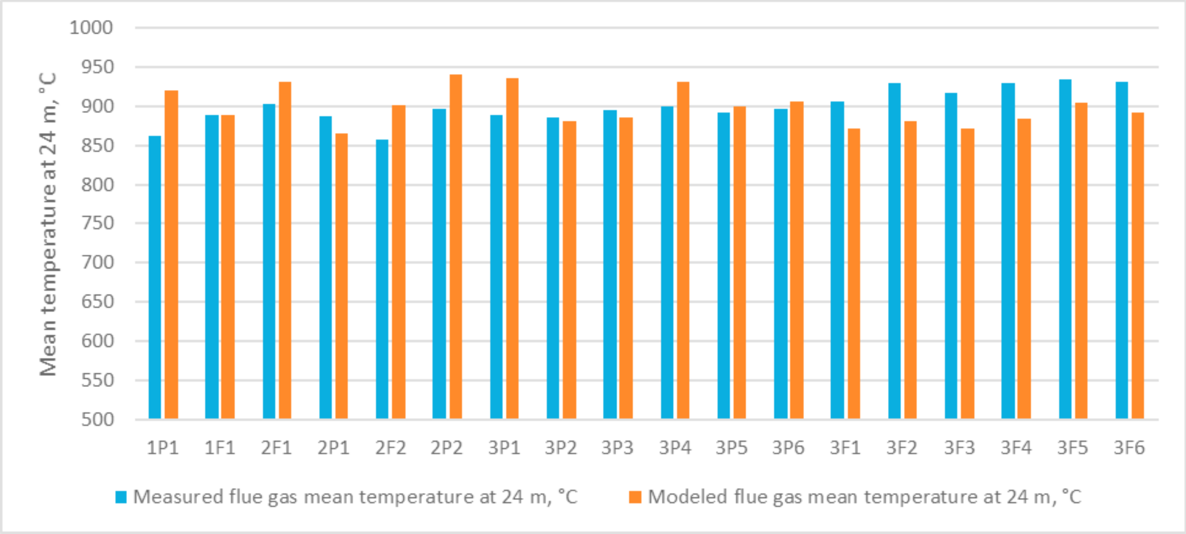

Fig. 2. Comparison between flue gas mean temperatures at 24 m as measured (in blue) by the plant instrumentation and estimated (in orange) by the model. The alphanumerical labels identify each measurement: the first digit refers to the number of the considered incineration line, the letter P (Partial) and F (Full) specify the load condition, while, the last digit tells the chronological order of execution.

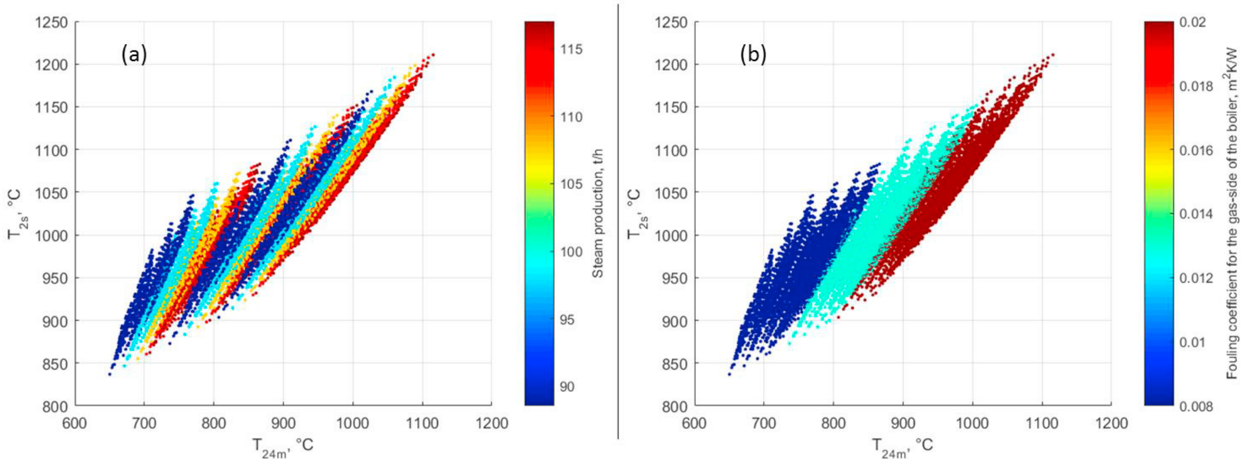

Fig. 3. T_{2s} vs. T_{24m} (both estimated) for all the simulations. Each point (representing one simulation) is colored depending on the value of a third variable: steam production for plot (a), and gas-side fouling coefficient for plot (b).

By adopting the minimum envelope of the cloud of points, one is always in the safest side, since the estimated T_{2s} is always lower than the actual one. However, this can lead to switching on auxiliary burners even when the actual T_{2s} is much above the normative threshold, with waste of expensive auxiliary fuel. To improve the T_{2s} estimation accuracy, the effects of other monitored variables must be considered. A variable is deemed to be adapt in formulating a control algorithm when it shows a clear effect on the minimum envelope of the cloud of points. This happens with oxygen concentration in secondary flue gas (x_{O2}), as it is shown in Fig. 4.

The minimum envelope of the cloud of points is always circa a straight line, with coefficients dependent on the oxygen concentration x_{O2}:

$$T_{2s}[°C] = (-0.86 \cdot x_{O2} + 0.4849) \cdot T_{24m}[°C] + (-2{,}175.5 \cdot x_{O2} + 731.14) \tag{2}$$

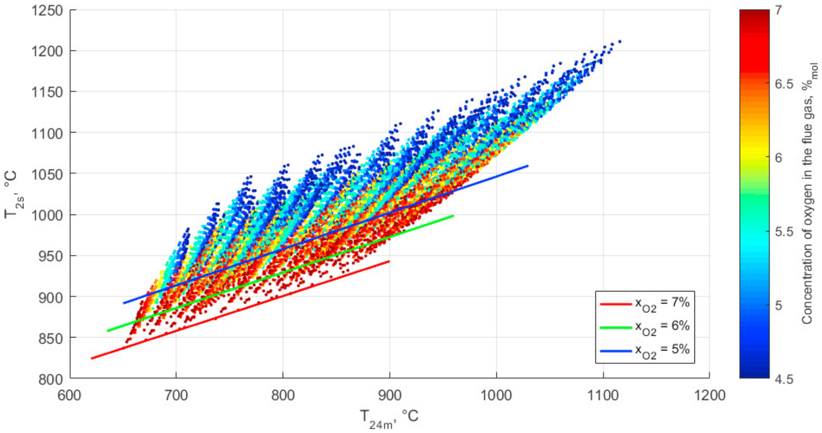

Fig. 4. T_{2s} vs. T_{24m} (both estimated) for all the simulations. Each point (representing one simulation) is colored depending on the corresponding concentration of oxygen in secondary flue gas. The three solid lines represent the second proposed algorithm for x_{O2} = 5, 6, $7\%_{Vol.}$ on wet basis.

6. Conclusions

The results of this work show that the T_{2s} is affected both by boiler load and gas-side fouling in the same way and for the same extent. Consequently, since gas-side fouling in the post-combustion zone is an uncontrollable variable, boiler load is not usable as input variable in a reliable algorithm.

Two algorithms are proposed for the case study considered: whilst the first one is a simple linear correlation between the T_{2s} and the T_{24m}, with the risk of significant underestimation of the T_{2s}, the second one improves significantly the prediction by using also the oxygen concentration in secondary flue gas. Other extensive investigations have been carried out by considering other monitored variables, however none of them influences the correlation between the T_{2s} and the T_{24m} as clearly as the oxygen concentration in secondary flue gas does.

Acknowledgements

The authors thank dr. Gaboardi and dr. Giorgio for the contribution given through their Master Thesis work [12].

References

[1] European Parliament and Council. Directive 2010/75. O.J. L 334, 17.10.2010, p. 17-119.
[2] Bundesministerium für Umwelt Naturschutz und Reaktorsicherheit (BMU). Bundeseinheitliche Praxis bei der Überwachung der Emissionen – RdSchr. D. BMU v. 13.06.2005 – Az.: IC I 2 – 45053/5. Published in: GMBI 2005 Nr.38, S.795.
[3] McBride BJ, Zehe MJ, Gordon S. NASA Glenn Coefficients for Calculating Thermodynamic Properties of Individual Species. NASA Tech Rep 2002-211556.
[4] Modest MF. Radiative Heat Transfer. 3rd ed. Boston: Academic Press; 2013.
[5] Bergman TL, Incropera FP, DeWitt DP, Lavine AS. Fundamentals of Heat and Mass Transfer. 7th ed. Hoboken: Wiley; 2011.
[6] VDI e. V., editor. VDI Heat Atlas. 2nd ed. Berlin: Springer-Verlag Berlin Heidelberg; 2010.
[7] Fellner J, Cencic O, Rechberger H. A new method to determine the ratio of electricity production from fossil and biogenic sources in waste-to-energy plants. Environ Sci Technol. 2007;41(7):2579–86.
[8] Westbrook CK, Dryer FL. Simplified Reaction Mechanisms for the Oxidation of Hydrocarbon Fuels in Flames. Combust Sci Technol. 1981;27(1–2):31–43.
[9] Kakaç S, editor. Boilers, Evaporators, and Condensers. Wiley-Interscience publication; 1991.
[10] Jegla Z, Bébar L, Pavlas M, Kropáč J, Stehlík P. Secondary combustion chamber with inbuilt heat transfer area - Thermal model for improved waste-to-energy systems modelling. In: 19th International Congress of Chemical and Process Engineering, CHISA 2010 and 7th European Congress of Chemical Engineering, ECCE-7. Technicka 2, 616 69 Brno, Czech Republic; 2010.
[11] Herapath RG, Peskett S. Excess oxygen and temperature control in furnaces, a dynamic modelling study. J Inst Energy. 1987;60:171–84.
[12] Gaboardi M, Giorgio A. Il requisito T_{2s} negli impianti di termovalorizzazione. Master Thesis (in Italian). Politecnico di Milano – School of Industrial and Information Engineering, Milan, Italy; 2016.