Proceedings of IMECE2008
2008 ASME International Mechanical Engineering Congress and Exposition
October 31-November 6, 2008, Boston, Massachusetts, USA

IMECE2008-67714

ANALYSIS OF TEMPERATURE AND RESIDENCE TIME OF THE EXHAUSTS IN THE COMBUSTION CHAMBER OF AN INCINERATOR PLANT

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ABSTRACT

The interest for energy recovery from waste incineration has increased over the years, in order to reduce the number of landfills and produce electricity and heat. At the same time, concern for the impact such processes have on the environment has also grown, and to reduce such an impact, new legislation is being enforced in Europe and Italy. In particular, important restrictions are imposed on the temperature of the exhausts in the combustion chamber, which must be kept above certain values for a given period of time, depending on the type of waste that is being incinerated. Such conditions can be rather difficult and certainly very expensive to monitor with acceptable accuracy. For this reason, in practical applications the temperature of the exhausts in the chamber is usually calculated through semi-empirical and approximate models that relate the temperatures in different sections of the chamber. In this work, the authors present a numerical approach for the analysis of such models that can be used to quantify the uncertainty on this type of measurement due to the common approximations used in full scale incineration plants. The analysis is based on the CFD simulation of the thermo-fluid-dynamic field in the combustion chamber of a full scale plant in Italy, whose results have verified based on a comparison with the data collected during an experimental campaign.

INTRODUCTION

Management of waste resulting from human activities is becoming one of the main problems in many industrialised countries. Waste incineration has become an important part of the waste management strategies adopted by many of these countries because of the possibilities to produce energy and heat in so-called Waste-to-Energy plants.

As for other energy conversion systems, incineration plants have to be built and operated by taking into account not only their efficiency but also the environmental impact due to the combustion. Among toxic substances to be controlled for their effect on human health, dioxin is one of the most dangerous. Dioxin is a general term that describes a group of hundreds of chemicals that are highly persistent in the environment, formed as unintentional by-products of many industrial processes involving chlorine, such as waste incineration, chemical and pesticide manufacturing, and pulp and paper bleaching [1-3].

Policies for restricting chlorine input to reduce dioxin formation in combustion systems have been adopted or recommended by national governments, professional associations, and advisory bodies as well as international treaties. This, mainly, as a consequence of the fact that numerous studies performed on laboratory- and pilot-scale combustion systems led to the conclusion that low chlorine input is associated with reduced dioxin formation, as indicated by dioxin concentrations in gaseous emissions and/or fly ashes.

Defining the relationship between chlorine input and dioxin formation in modern, full-scale waste combustors, instead, revealed admittedly a very difficult task.

Waste incinerators, on the other hand, currently receive the bulk of discarded PVC and other chlorine sources that are deliberately burned. This means that the economic and political consequences of restricting chlorine input to waste incinerators are much more far-reaching than restricting chlorine inputs to other combustion systems, such as lead smelters.

It follows that, while in full scale plants, as iron/steel production, sinter plants, primary and secondary copper production, secondary aluminum production, utility and industrial boilers, reducing the inputs of chlorine and chlorine-containing materials is, nowadays, an effective and low-cost method for reducing dioxin, in waste incinerators other factors must be considered, whose influence over dioxin formation is far greater. Wikstrom and Marklund clearly state that "*the most important variable for changes in the PCDDs/Fs [dioxins] ... formation was disturbance in the combustion condition and not the variation in chlorine content of the fuel*" [4]. Nowadays, it is well assessed that control of the dioxin levels in the exhausts of waste incineration plants can be reached mainly by controlling the thermo-fluidynamic processes occurring within the combustion chamber. Regulation laws have been enforced in many countries in order to introduce stringent operating conditions and set minimum technical requirements for incineration plants [5-7].

It is evident that fulfilment of these restrictions is hard to be assessed, either in the phase of plant design, or in the course of actual operation. An accurate design of the combustion chamber would require a detailed knowledge of the distribution of the thermo-fluidynamic variables as well as of the chemical composition of the gases under the prescribed operating conditions. Collecting the needed information from actual operating plants, on the other hand, would entail extremely high costs of both the needed measurement instrumentation and also of the possible modifications to be realised on the plant for its installation.

From a practical point of view, semi-empirical algorithms are often employed to correlate the variable to be controlled by regulations to other variables that can be more easily measured. As an example, local variables, such as the temperature in certain points of interest, are derived from global ones, such as the amount of water vapour produced by the whole plant. Obviously this kind of approach relies on simplified descriptions of the thermo-fluidynamic field in the combustion chamber and is intrinsically highly dependent on the considered plant and the relevant operating conditions, and it is strongly affected by uncertainties which are hardly quantified experimentally.

The present paper proposes the use of a quite simple numerical approach, suitable to be applied both in the phase of assessment of the controlling parameters and during the plant operation, which allows to determine the value of the variables object of law regulations. The method also proves to be useful to identify more clearly some of the critical aspects of the simplified methods generally employed in the common practice.

CASE STUDY: AN ITALIAN INCINERATION PLANT

Object of the present study is the power generation plant situated in Italy, in San Vittore, where the combustion of Refuse Derived Fuel (RDF) waste is exploited to supply heat to a steam Rankine cycle.

A short description of the plant and the existing measurement devices, is given in the following.

The technical characteristics of the combustion chamber allow the use of fuels with Lower Heating Values (LHVs) in the range between 10000 and 20000 MJ/kg. The main characteristics of the line of combustion and energy conversion are presented in Tab. 1.

After being weighted, the waste is stored in two reservoirs from which it is loaded on conveyor belts that bring it toward the furnace grid. Here the waste is invested from the bottom by a primary air flow distributed by twelve nozzles. The combustion takes place in the solid bed and continues in the gaseous phase in the upper part of the combustion chamber of the thermal recovery plant, where a secondary air flow is blown into the chamber. The heavy ashes formed during the combustion in the solid phase are collected under the grid. The secondary air flow is made through three series of nozzles placed just downstream of the restricted section of the combustion chamber (hereafter called venturi section). Under particular conditions, such as the start-up of the plant or the use of waste with a LHV particularly low, two auxiliary burners fuelled by methane are activated in order to maintain the temperature of the produced steam to the values prescribed by the plant design.

Parameters	**Values**
Combustor power	52 MW
Flow rate of the produced steam	54 t/h
Exhausts temp. at the chimney	140 °C
Electric power generated	12.5 MW
Total surface of the grid	60 m^2
Waste flow rate	12 t/h
Primary Air	
Flow rate (normal conditions)	6.0×10^4 m^3/h
Total pressure	0.03 bar
Nominal power	160 kW
Secondary Air	
Flow rate (normal conditions)	4.8×10^4 m^3/h
Total pressure	0.05 bar
Nominal power	250 kW

Tab. 1: Plant characteristics.

The combustion products are treated before being exhausted in the atmosphere through a semi reactor where the absorption of acid gases (HCl, SO_2, HF) and the simultaneous removal of heavy metals and dioxins/furans are realised. In the reactor, the combustion products are sent through filters for the removal of still suspended ashes. A process of NO_x reduction of non-selective catalytic type (SNRC) with injection of a solution of urea is also realised.

The plant is equipped with various measurement devices, a part of which was exploited by authors during the experimental campaign conducted on the real working plant. In order to describe the available instrumentation, the plant can be subdivided in two main parts. The first consists of the combustion line of the waste, whereas the second one is the working line of steam in the Rankine cycle.

The two lines are obviously strictly linked one to each other. This has to be taken into account especially if the temperature of the combustion products after two seconds has to be calculated according to a semi-empirical procedure as the one which is currently in use. The part relevant to the waste combustion is described in the following in some detail, in order to better understand the experimental data suitable to be collected in each of them.

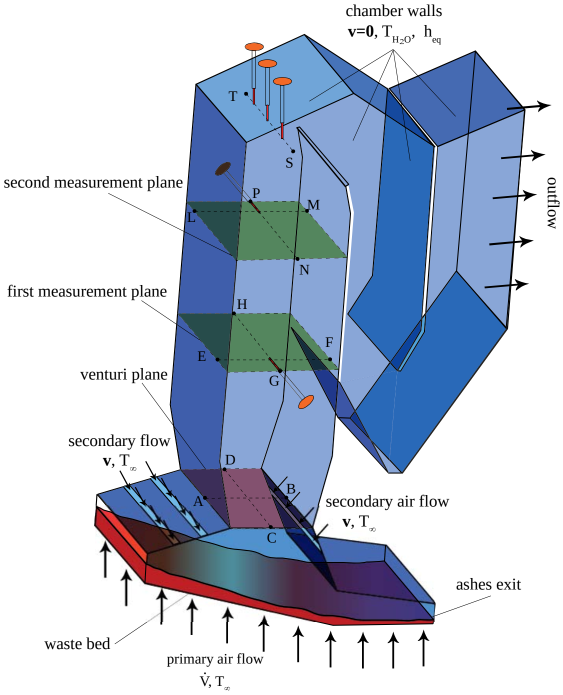

Fig. 1: Computational domain and measurement points of the vertical channels of the incinerator combustion chamber.

Fig. 1 presents a schematisation of the line of waste combustion where one may follow the fuel since its introduction in the furnace until the exhaust in the atmosphere in the form of combustion products. The figure also reports the positions of some of the measurement instruments installed in the first vertical channel for verification of the fulfilment of the restriction on the temperature of the exhausts. Obviously, the plant is equipped with a large number of instruments that monitor several quantities used for an effective plant operation and to control the amount of pollutants emitted in the atmosphere.

Some of these are: a venturi meter, that measures the total mass flow rate of primary air; other twelve venturi meters, that allow to quantify the single mass flow rate through each nozzle; a differential pressure gauge that measures the pressure close to the venturi meter.

The secondary air is introduced in the combustion chamber through a series of nozzles, that are also sketched in Fig. 1. Two of these series are located to the left of the venturi section, while the other is located to the right. On each of the inflow lines a volumetric flow meter is installed.

In the first vertical channel of the boiler, where the heat exchange is mainly of radiative type, measurements of temperature are effected on four different levels: two points of measurement are located about two meters above the grid; other six points, three for each side, just above the auxiliary methane burners, on a first measurement level; six points are approximately twenty-four meters above the grid, on a second measurement level, and, finally, three points are positioned on the top of the boiler, on the ceiling, for a total of seventeen possible contemporary acquisitions. In correspondence of the measurement points wells of 18 mm in diameter host thermocouples. The three thermocouples of "type K" (shown in Fig. 1 along line T,S), measure the temperature values that are used to calculate the temperature of the combustion products two seconds after the inflow of secondary air.

Downstream of the three vertical channels presented in Fig. 1, in an horizontal channel containing a number of heat exchangers, the temperature of the exhausts is still monitored by "type K", as well as before they are sent to the treatment section. After passing through this cleaning section, combustion products go through a fan which ensures a slight depression in the combustion chamber. Finally, in the chimney the temperature, pressure and mass flow rate are measured, respectively by means of a thermo-resistance, a differential pressure gauge and a venturi meter.

The composition of the exhausts at the chimney exit is detected by a scattering technique, measuring the concentration of ashes and a photometer measuring the concentrations of H_2O, CO, CO_2, NH_3, NO_x, SO_2, HCl, HF and O_2.

Two extra N-type thermocouples have been installed on different levels along the first vertical channel of the combustion chamber (Fig. 1), during the experimental campaign described later in the paper, in order to verify experimentally the temperature distribution along the chamber.

METHODOLOGIES FOR ASSESSING THE FLULFILMENT OF LAW REGUALTIONS OF WASTE INCINERATION PLANTS

As mentioned in the introduction, a European directive [5], states that "… *Incineration plants shall be designed, equipped, built and operated in such a way that 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 unfavourable conditions, to a temperature of 850 °C, as measured near the inner wall or at another representative point of the combustion chamber as authorised by the competent authority.* ….". The Italian government has consequently implemented specific laws [6, 7], under which all incineration plant are currently operated.

From a practical point of view, it is clear that fulfilling this regulation would imply the need to follow all the combustion products particles along their trajectory in order to make sure that their temperature stays above 850 °C for at least two seconds after the secondary air injection.

There are obviously many possible scenarios for the zone where the temperature may have to be measured: as a consequence of two different velocity fields of the particles in the section placed just downstream the injection of secondary air. The position assumed by the fluid particles can change quite extensively. In other words, not only measuring the temperature for the whole interval of time of two seconds after the last injection of air, but also defining the particles position at the end of this interval is a difficult task strongly affected by the plant operating conditions. Moreover, one may note that installing the necessary instrumentation to continuously measure the temperature in the entire zone of interest would be very expensive.

It follows that, usually, the verification of compliance of a plant with the prescribed normative is made on the basis of the temperature measured in positions such as the ceiling of the combustion chamber, and using simplified algorithms that allow to relate these measurements to the value of the temperature of the combustion products two seconds after the last air injection. These algorithms are generally developed at the design stage of the plant, and are based on approximations, whose influence must be properly assessed case by case. The correlation used for the plant previously described is presented in Fig. 2, where the difference between the temperature of the exhausts two seconds after the last air injection (T_{2s}) and the temperature measured at the ceiling of the chamber ($T_{ceil.}$) is plotted against the total mass flow rate of vapour produced at the plant.

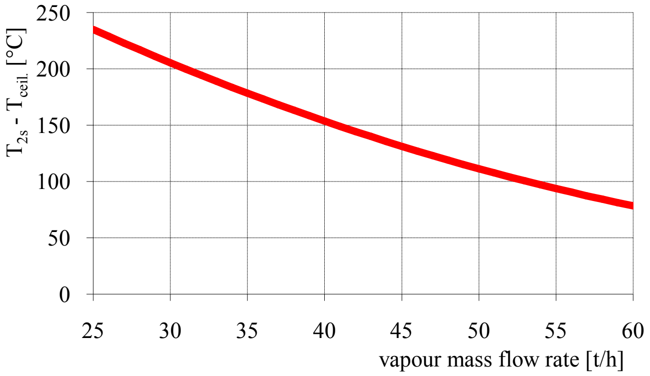

Fig. 2: Semi-empirical correlation for the temperature difference in the exhausts of the chamber and the total vapour produced in the plant.

Such correlation is obtained through an energy balance on the first vertical channel of the combustion chamber, and the theory used for heat exchangers design.

Some of the assumptions commonly used in this type of analysis include stationary and one-dimensional conditions, negligibility of the pressure losses in the channels. However, in order to better understand the limitations of the assumptions made, it is important to underline that:

- the correlation depends on the plant considered and its operating conditions, and should therefore be verified periodically;
- the total mass flow rate of vapour produced in the plant, presented in Fig. 2, is not fully relevant to the energy balance in the first channel of the chamber; in fact, varying the ratio between primary and secondary air, it would be possible to obtain the same amount of vapour produced in the plant, but with a different temperature distribution;
- the geometry of the combustion chamber and the multi-dimensional characteristics of the thermo-fluid-dynamic field are clearly in contrast with the assumption of mono-dimensionality.

For this reasons it is important to investigate different options for the verification of the law restrictions on the temperature of the exhausts. In particular, it is possible to obtain a more detailed description of the temperature distribution in the chamber using Computational Fluid Dynamic (CFD) techniques [8-17]. In this work, the authors present the results of this type of model developed for the simulation of both the solid and gaseous combustion that occur in an incineration plant [17].

The details of the numerical simulation of the thermo-fluid-dynamic processes occurring in the combustion chamber of the San Vittore plant are not presented here for the sake of brevity. Solid and gaseous combustion are solved separately using different codes. The strong interdependency between the solid phase combustion on the furnace and the combustion in the gaseous phase, occurring in the upper part of the combustor are taken into account.

The model proposed for the simulation of combustion in the solid phase is based on the assumption that the waste bed can be considered as a porous medium, macroscopically represented by four elements, namely humidity, volatile matter, char and ashes. The solid phase combustion process is divided into four successive sub-processes: drying, pyrolysis, volatile matter combustion and char gasification, with the consequent formation of ashes. Each of the processes determines a volume reduction of the waste bed, which leads to a change in the bed porosity, hence to a reduction of the bed height. The mathematical model that describes all these processes is a system of equations representing the conservation of mass, momentum, energy, and chemical species in the porous medium, solved in this work using a code named FLIC, developed at the University of Sheffield [12-15]. Further details of the code are available in the literature.

The determination of the waste characteristics represents one of the major sources of uncertainty in the present approach. The waste composition is not constant, but depends on several factors, not easily and continuously monitored. Therefore, a sensitivity analysis has been carried out in ref. [17] with the aim of evaluating the dependence of results on the waste composition. A similar behaviour of wastes having a similar macroscopic analysis was observed. The results presented in this work refer to the waste of composition reported in Tab. 2, with a lower calorific value of 16189 kJ/kg.

Combustion in the gaseous phase is simulated using the commercial code FLUENT. This code allows to numerically solve the balance equations for mass, momentum and energy for stationary, turbulent, reacting flows, characterized by Mach numbers much lower than one. These equations are widely consolidated for the analysis of these kind of problems, and are not introduced here for brevity. The interested reader may refer to the available literature [18].

Approximate Analysis (mass %)

Humidity	Volatile matter	Char	Ashes
21.5	32.8	37.7	8

Ultimate Analysis (mass %)

C	H	O	N	S	Cl
68.73	3.25	27.05	0.223	0.251	0

Tab. 2: RDF Composition (mass %)

The impossibility to define chemical and physical properties of the equivalent fuel produced from the combustion of the waste solid bed (C_mH_n) leads to the need of an alternative approach for the definition of the hydrocarbon participating the gaseous combustion. Only propane (C_3H_8) is considered here as product of solid combustion entering the secondary combustion chamber. This fuel, among paraffinic hydrocarbons, presents the closest molecular weight to the equivalent fictitious hydrocarbon resulting from waste analysis.

It follows that the reactions of combustion in the gaseous phase can be described using the following reduced kinetic scheme, made of two steps:

$$C_3H_8 + 3.5O_2 \rightarrow 3CO + 4H_2O$$

$$CO + 0.5O_2 \rightarrow CO_2$$

The source term in the mass balance equation for each single specie is estimated by determining the reaction rate through Arrhenius type formulas, of assigned pre-exponential factor and activation energy. The interaction between chemistry and turbulence is treated by using the model of Magnussen and Hjertager [19, 20], according to which the chemical reactions occur on temporal scales smaller than those characteristic of turbulence. In the case considered, turbulence is the slowest phenomenon, hence it can be considered to control the evolution of the combustion process.

In order to verify the validity of the assumptions usually made in systems like the one studied in this work, simulations are carried out both considering and neglecting the effect of gravity on the mean flow, which corresponds to mixed and forced convection, respectively. The specific heat capacity pressure of the mixture is assumed to vary with the temperature, according to a polynomial law [21].

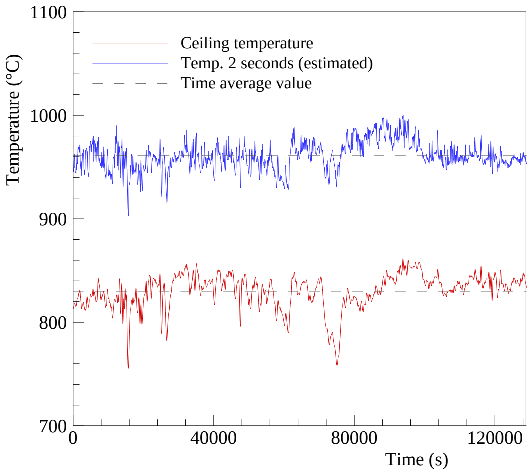

Fig. 3: Comparison of the mean temperature measured at the ceiling and the temperature after two seconds calculated with the correlation of Fig. 2.

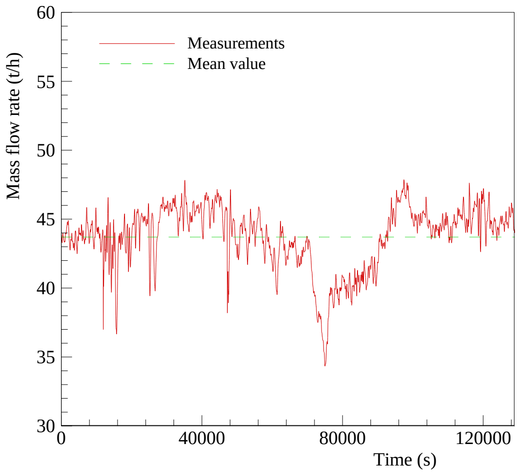

Fig. 4: Total mass flow rate of vapour produced at the plant.

The boundary conditions for the proposed model account for the presence of the: i) solid bed, obtained from the numerical analysis of solid combustion; ii) energy exchange between the exhausts and the combustion chamber walls; iii) secondary air flow, according to the flow rate measured at the plant. About the latter condition, three inflow boundaries are considered, the areas of which are equivalent to the sections of the nozzles.

As previously said, the solid bed thickness, obtained as a result of the solid waste simulation code, determines the shape of the lower section (inflow section) of the computational domain. Inflow conditions are also derived from the solid waste simulation. The boundary conditions on the combustion chamber walls are set to zero velocity, with standard wall functions. The energy exchange is set using a simplified condition, equivalent to the actual conditions in the full scale system. In fact, proper thermal boundary conditions can be obtained through the evaluation of the conductive field through the walls of the chamber, in order to derive an equivalent one dimensional boundary condition. Such condition represents the continuity of energy transferred from the exhausts to the water that circulates in the pipes of the boiler, and takes into account all the heat transfer modes across the wall of the chamber. Since the walls of the boiler, in the first channel are partially covered by refractory material, two different heat transfer coefficients must be considered. Fouling on the walls of the boiler is also taken into account.

A mesh sensitivity analysis was carried out in order to assure that the solution did not depend on the chosen grid. The results obtained from the simulations where compared to the temperatures measured in different sections of the chamber, in order to verify the proposed numerical model [17].

ANALYSIS OF THE RESULTS WITH THE TWO METHODOLOGIES USED

The measurement of the temperature of the exhausts in the combustion chamber of an incineration plant is far more complicated than the measurement of other operating parameters, such as the amount of pollutants in the exhausts. This section presents the results of the application of the two methodologies presented previously for the calculation of the temperature of the exhausts two seconds after the last air injection in the chamber.

Regarding the experimental campaign, Fig. 3, shows the mean value of the temperatures of the exhausts measured at the ceiling of the chamber ($T_{ceil.}$) over a period of time of about 36 hours. The reported values have been acquired every ten seconds, which is also the time constant of the three "K-type" thermocouples used. The uncertainty of these measurements has been estimated to be between 5 and 8° C. The same figure presents also the temperature of the exhausts two seconds after the last air injection (T_{2s}), calculated using the semi-empirical model presented in Fig. 2. The value of the total mass flow rate of vapour measured in the plant, which is used in the semi-empirical model, is presented in Fig. 4 for the same period of time. The figures, analysed together, show an interesting result. The exhausts temperature after two seconds, T_{2s}, appears to oscillate less that the temperature of the ceiling, $T_{ceil.}$, with respect to their mean values. This is not what was expected, as the instabilities due to the combustions should have a smaller effect as the exhausts move away from the combustion zone. The reason for the behaviour of the temperature in Fig. 3 should be found in the algorithm used to estimate the T_{2s}. As the mass flow rate increases, the temperature difference obtained from in Fig. 2, decreases and therefore, the correspondent drop in the temperature of the ceiling is not followed by a drop of the T_{2s}. This same consideration can be used as an explanation for the higher “noise” in the measurement of the temperature T_{2s} respect to the T_{ceil}.

An example of the results obtained with the numerical model is given in Figg. 5 and 6, where the temperature distribution in different sections of the chamber are presented. In particular, Fig. 5 refers to the case of forced convection, while Fig. 6 is obtained considering the buoyancy effect (mixed convection) on the thermo-fluid-dynamic field in the chamber. Both figures show the temperature in the vertical middle plane of the chamber, in three horizontal sections, the venturi, the first and second measurement sections (shown also in Fig. 1), and the surface of the waste bed. These figures already show that some of the assumptions used in the development of semi-empirical models, such as the hypothesis of forced convection, do have an impact on the results produced. In fact, the temperature distribution in the chamber is quite different in the two cases considered. In order to show these effects on the measurement of the T_{2s}, it is possible to calculate the trajectory of the particles that at a certain instant in time are in the venturi section, which is immediately downstream the last air injection. For these particles it is the possible to calculate the temperature along the trajectory, and verify if this temperature stays above 850°C for at least two seconds as required.

Figg. 7 and 8 show the results of this verification. For about 2000 particles that flow through the venturi section at a given instant of time, assumed to be the initial, these figure present the trajectory and the related temperature along such trajectory. The same figures also present the temperature of the particles at the initial time (in the venturi section). From these figures it is clear that the temperature of the particles that are initially near the wall on the left of the picture are far below the prescribed temperature. In fact, the temperature of these particles is influenced by the secondary air injection, whose temperature is close to 30° C.

However, following the particles along their trajectories, it is possible to notice that these are heated by the neighbouring hot particles, and reach temperatures 1100K near the ceiling of the chamber. On the other hand, as regards the case of mixed convection, some of the particles that are initially in the venturi section, under the effect of gravity, move towards the waste bed, in the lower part of the combustion chamber. These recirculation zones are maintained at a low temperature (by far lower than 850°C) by the continuous incoming secondary air. Near the ceiling of the chamber, the trajectories followed by the particles differ from the case of forced convection showing larger recirculation zones also in this area of the chamber. In any case, these figures confirm that, in the study of the phenomena occurring in the combustion chamber, the effects related to the gravitational forces cannot be neglected.

The results presented in Figg. 9 and 10 confirm this affirmation, in fact these figures present a comparison between the results obtained numerically using the present model and those derived from the semi-empirical correlation used at the incineration plant of San Vittore for the calculation of the exhausts temperature after two seconds. Such comparison is presented in terms of position of the particles after two seconds after the last air injection and the related temperature in that position. One may notice that, in the case of forced convection, the position predicted by the semi-empirical model somehow well approximates the one obtained numerically, even though it cannot predict the non-uniformity of motion as consequence of the gas viscosity.

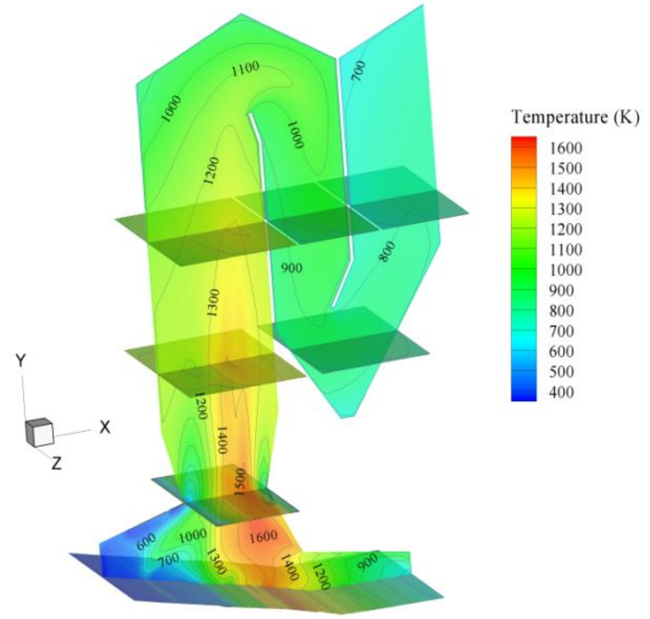

Fig. 5: Temperature distribution in the combustion chamber in the case of forced convention.

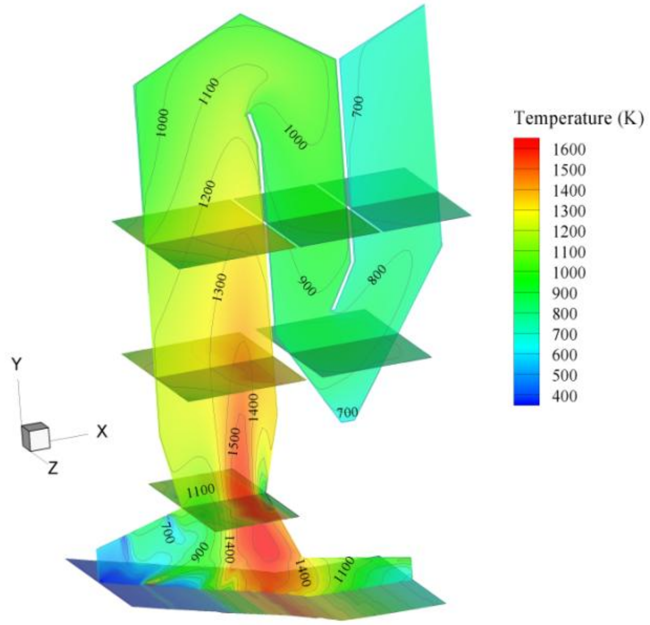

Fig. 6: Temperature distribution in the combustion chamber in the case of mixed convention.

Moreover, in terms of temperature distribution in the chamber, for the case of forced convection, the temperature of the exhausts calculated with the numerical model is well approximated by the value calculated using the semi-empirical model (that corresponds to the mean value of about 1230K presented in Fig. 4). However, in the case of mixed convection, the same data presented in Fig. 10 show that the particles position is really more spread along the vertical axis of the first channel. In particular, in this case, due to the buoyancy forces acting on the fluid, some of the particles are even found below the venturi section, as mentioned before and clearly shown in Fig. 8. Other particles have reached the area near the ceiling of the chamber already after two seconds, as it can be seen in Fig. 10. Regarding the temperature of the exhausts, it is noticed that most of the particles after two seconds has not reached the value predicted by the semi-empirical model, especially in the central part of the chamber, which is affected be the buoyancy forces acting in the fluid. Finally, the particles that are found to be at the lowest temperature after two seconds should not give any problem in terms of verification of the law restrictions, as they are in the recirculation area below the venturi.

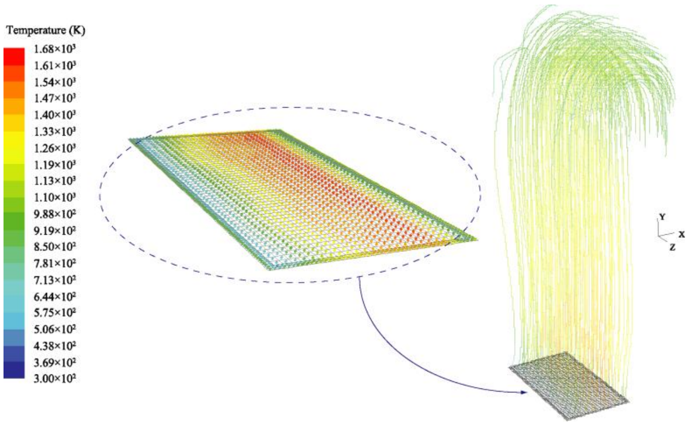

Fig. 7: Particles trajectories from the venturi section for the case of forced convention.

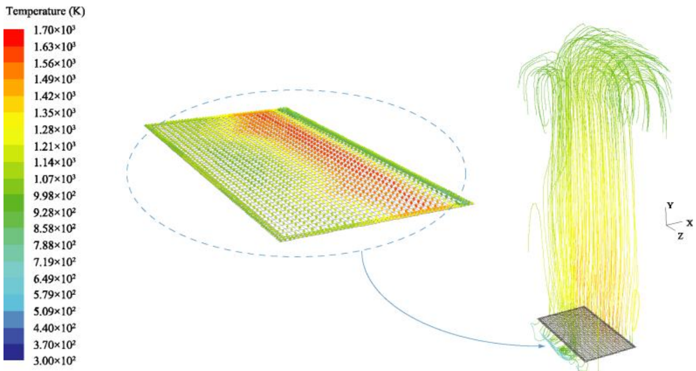

Fig. 8: Particles trajectories from the venturi section for the case of mixed convention.

It is important to notice that the methodology used at the San Vittore plant is commonly used in other incineration plants and accepted by the competent authorities. In fact, law restrictions are probably set on the basis of considerations derived from semi-empirical models instead of deep methods of analysis, like the one presented here.

In the authors opinion, additional guidance would be needed about where to perform measurements of temperature in the combustion chamber, without leaving to the competent authority the responsibility to specify which can be considered as "*... another representative point of the combustion chamber*" (as authorised by the competent authority).

CONCLUSIONS

This paper presents the results of a numerical and experimental investigation of the thermo-fluid-dynamic field in the combustion chamber of an incineration plant for RDF, developed in order to verify that the restrictions imposed on the temperature of the exhausts two seconds after the last air injections are met.

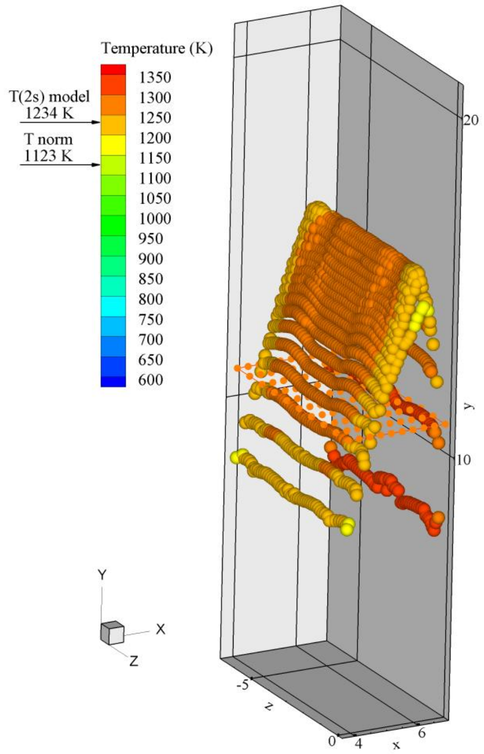

Fig. 9: Comparison of the numerical and semi-empirical models: Position (m) of the particles after two seconds with the related temperature (K), for forced convection.

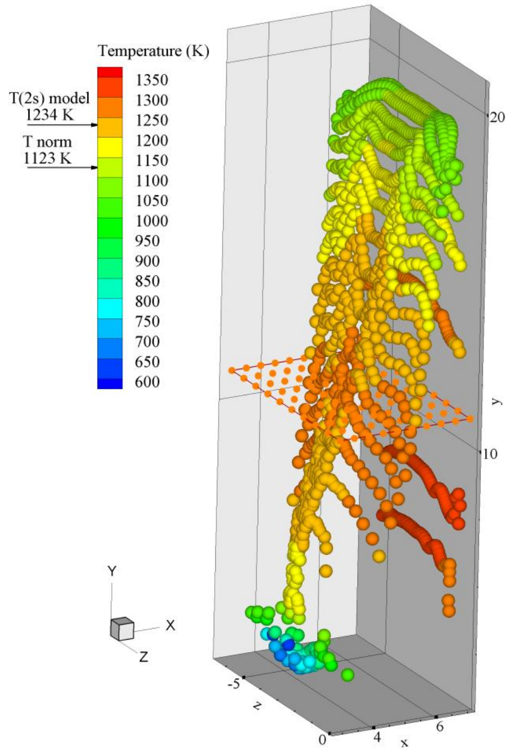

Fig. 10: Comparison of the numerical and semi-empirical models: Position (m) of the particles after two seconds with the related temperature (K), for mixed convection.

The experimental campaign has been carried out on–site at the Italian incineration plant of San Vittore del Lazio. The results obtained have been used to analyse the methodology currently used at the plant, which is based on a semi-empirical correlation between the temperature of the exhausts at the ceiling of the first vertical channel of the chamber and their temperature two seconds after the last air injection.

The limits of this methodology have suggested the need to use CFD techniques to investigate into more details the temperature distribution in the chamber. The experimental results have also been employed to verify the numerical model used in this work.

The numerical model has allowed the authors to investigate both the solid and gaseous combustion in the chamber, and obtain the detailed description of the phenomena occurring in the chamber.

Based on these results, it possible to draw the following conclusions:

- the procedure that is currently employed at the San Vittore plant allows to estimate the temperature of the exhausts in first vertical channel of the chamber, but with uncertainties that are not negligible;
- for a fuel with the characteristics presented, and under the same operating conditions as those simulated in this work, it is not possible to assure that the restrictions imposed by the law are always met.

However, the proposed analysis has also highlighted some of the limitations of the restrictions imposed by the law. In fact, these are very difficult to be verified without the proper instrumentation, which would make the whole process non sustainable from the economical point of view.

Alternatively, it is possible to use the type of analysis presented in this work, but some of the parameters needed for the simulations, such as the compositions of the RDF, would have to be continuously monitored on the plant.

REFERENCES

[1] H. Huang, A. Buekens, On the mechanism of dioxin formation in combustion processes, *Chemosphere*, vol. 31 (9), pp. 4099–4117, 1995.

[2] G. McKay, Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration: review, Chemical Engineering Journal, vol. 86, pp. 343–368, 2002.

[3] P.A. Bertazzi, D. Consonni, S. Bachetti, M. Rubagotti, A. Baccarelli, C. Zocchetti, A.C. Pesatoril, Health Effects of Dioxin Exposure: A 20-Year Mortality Study, American Journal of Epidemiology, vol. 153 (11), pp. 1031–1044, 2001.

[4] E. Wikstrom, S. Marklund,. The influence of level and chlorine source on the formation of mono- to octa-chlorinated dibenzo-p-dioxins, dibenzofurans and coplanar polychlorinated biphenyls during combustion of an artificial municipal waste, Chemosphere, vol. 43, pp. 227-234, 2001

[5] Directive 2000/76/EC of the European Parliament and of the Council of 4 December 2000 on the incineration of waste.

[6] Decreto Legislativo del 05/02/1997 n.22, "Attuazione delle direttive 91/156/CEE sui rifiuti, 91/689/CEE sui rifiuti pericolosi e 94/62/CE sugli imballaggi e sui rifiuti di imballaggio" (in italian).

[7] Decreto Legislativo del 05/02/1997 n.22, "Attuazione delle direttive 91/156/CEE sui rifiuti, 91/689/CEE sui rifiuti pericolosi e 94/62/CE sugli imballaggi e sui rifiuti di imballaggio" (in italian).

[8] Ryu C.K., Choi S. 3-Dimensional Simulation of air mixing in the MSW Incinerators, Combustion Science and Technology 1996; 119: 155-70.

[9] Ryu C.K., Shin D., Choi S. Combined simulation of Combustion and Gas Flow in a Grate-Type incinerator, J. Air & Waste Manage Assoc. 2000; 52: 174-85.

[10] Shin D., Choi S. The combustion of simulated waste particles in a bed, Combustion and Flame 2000; 121: 167-80.

[11] Goh Y.R., Lim C.N., Zakaria R., Chan K.H., Reynolds G.R., Yang Y.B. Mixing, modelling and measurements of incinerator bed combustion, J. of Process Safety Env. Prot., Trans. Inst. Chem. Eng. 2000; 78: 21-32.

[12] Yang Y.B., Yamauchi H., Nasserzadeh V., Swithenbank J. Effects of fuel devolatilisation on the combustion of wood chips and incineration of simulated municipal solid wastes in a packed bed, Fuel 2001; 82: 2205–21.

[13] Yang Y.B., Goh Y.R., Zakaria R., Nasserzadeh V., Swithenbank J. Mathematical modelling of MSW incineration on a travelling bed, Waste Management 2002; 22: 369-80.

[14] Yang Y.B., Sharifi V.N., Swithenbank J. Effect of air flow rate and fuel moisture on the burning behaviours of biomass and simulated municipal solid wastes in packed beds, Fuel 2004; 83: 1553-62.

[15] Yang Y.B., Lim C.N., Goodfellow J., Sharifi V.N., Swithenbank J. A diffusion model for particle mixing in a packed bed of burning solids, Fuel 2005; 84: 213-25.

[16] Peters B. Thermal conversion of Solid Fuels, Wit Press Southampton, Boston, USA, 2003.

[17] M. Costa, M. Dell'Isola, N. Massarotti, M. Petea, L. Stabile, A. Viola, Numerical analysis of the thermo-fluid-dynamic field in the combustion chamber of an incinerator plant, Proceedings of the 20th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS), Padova (Italy), June 25-28, Vol. II, pp. 1553-1561, 2007.

[18] Chung T.J. Computational Fluid Dynamics, Cambridge University Press, 2002.

[19] Magnussen B.F., Hjertager B.H. On mathematical models of turbulent combustion with special emphasis on soot formation and combustion, Proceeding of the 16th International Symposium on Combustion, The Combustion Institute, Pittsburgh, 719-729, 1976.

[20] Magnussen B.F. On the Structure of Turbulence and a Generalized Eddy Dissipation Concept for Chemical Reaction in Turbulent Flow, Proceeding of the 19th ALAA Meeting, St. Louis, 1981.

[21] Incropera F.P., DeWitt D.P. Fundamentals of Heat and Mass Transfer, 5th ed., J. Wiley & Sons, USA, 2002.