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To cite this article: F. Arpino *et al* 2021 *J. Phys.: Conf. Ser.* **1868** 012023

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A 0D-3D approach for numerical analysis of waste to energy plants: a case study.

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Abstract. In this paper the authors present a 0D-3D approach for numerical modelling of a waste-to-energy plant located in Italy in different operating conditions. This innovative methodology combines a 0D lumped parameters model, able to describe the processes of solid and gaseous combustion and the heat transfer within the first radiant channel, with a detailed 3D CFD simulation of the thermo-fluid-dynamic field within the plant combustion chamber. Results from the 0D model allow the definition of input data and boundary conditions for detailed 3D CFD simulation of the thermo-fluid-dynamic field within the plant combustion chamber. In this way, the T_{2s} temperature can be determined according to actual definition of European legislation. The developed numerical tool is generally applicable to any waste-to-energy plant, and is here applied for the characterization of different operating conditions of an Italian WTE plant. The analysis allows the verification of the constraints imposed by the European legislation on the temperature of the combustion products and the identification of any issues related to the plant operation. In order to demonstrate the performance of the proposed numerical modelling approach, in this paper the authors present and discuss the results obtained by applying the model to one day-averaged operating condition of a WTE plant in Italy. Input parameters are obtained from available measurements and numerical results are validated against experiments showing a good agreement. Data and results in this paper are presented in a normalized form for confidentiality.

1. Introduction

Waste management depends on various aspects, from the level of technological development, to the availability of areas for landfills and even to the local population cultural level [1]. In 2011 the European Commission (EC) published a report on “Member States performance in the prevention and recycling of waste”, showing that main long-term goal consists of becoming a “recycling society”, based on a “resource efficient economy” [2]. Energy recovery from waste incineration represents an important waste management process, but in order to avoid the formation of pollutants a proper combustion control is needed. In fact, in the last decades research activity showed that particulate carbon acts as major carbon source for dioxins, that inorganic chlorides act as chlorine source, and that the presence of oxygen is essential [3]. Favoured precursors for dioxins formation are the products of incomplete combustion and a proper combustion control significantly reduces dioxin formation. To this aim, European legislation 2000/76/CE prescribes that, for non-hazardous wastes, the temperature of the gaseous combustion products, referred in the following as T_{2s} , must be kept above 850 °C for at least 2 seconds. The respect of the imposed temperature constraint would allow thermal destruction of dioxin precursors [4]. Nevertheless, it would require the ability to follow any fluid particle in



the combustion chamber for at least 2 seconds, measuring its temperature at the same time. Since such measuring approach is unfeasible, the T_{2s} is usually experimentally estimated performing temperature measurements in correspondence of given combustion chamber location, basically assuming that fluid particles follow a straight path with no recirculation inside the combustion chamber. In a WTE plant operation, the T_{2s} is usually continuously verified in situ by employing simplified 0D models, typically based on the use of empiric correlations obtained from measurements performed on similar plants, and assuming a reference biomass fixed composition. Such an approach offers the advantage to be relatively simple and not demanding from the computational point of view. Nevertheless, its ability to actually predict the T_{2s} temperature depends on the fluid velocity field within the combustion chamber and obviously on the actual Refuse Derived Fuel (RDF) composition [5–7]. Such limitation could be overcome by validated 3D numerical simulations, that offer the ability to have detailed information about spatial and temporal distribution of quantity of interests in the combustion chamber [2,5–9]

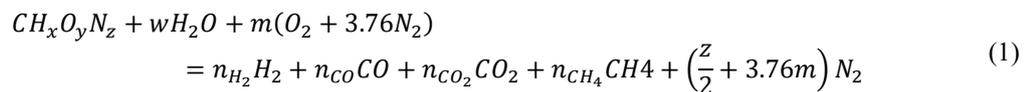
In the present paper the authors describe the results of a novel 0D-3D numerical approach applied to reproduce operating averaged steady state conditions of a real life WTE plant in Italy. This modelling approach combines a simplified thermodynamic 0D lumped parameters model, able to describe the processes of solid and gaseous combustion and the heat transfer within the first radiant channel, with a detailed 3D CFD simulation of the thermo-fluid-dynamic field within the plant combustion chamber. The general 0D model is not based on the use of empirical or semi-empirical correlations, deriving from experimental data regressions and calibrated for a specific co-incineration plant, but on the actual Refuse Derived Fuel (RDF) composition and the real flow rates and reagents temperature (primary and secondary air) in input to the system. Besides, results from the 0D model allow the definition of input data and boundary conditions for detailed 3D CFD simulation of the thermo-fluid-dynamic field within the plant combustion chamber. In this way the T_{2s} temperature can be determined using a more efficient and complete methodology.

The input parameters were determined from measurements and the obtained numerical results were validated against experimental data, showing a good agreement. In this paper the authors show obtained results for one averaged operating condition of the WTE plant, referred to an operating time of one day.

Because of confidentiality constraint, input data used for simulations are not reported in this paper, while obtained results are presented in the following in a non-dimensional form.

2. The proposed 0D-3D modelling approach

The proposed 0D-3D modelling approach is based on contemporary use of a 0D-1D thermodynamic model alongside with a detailed not reacting 3D model based on modern computational fluid dynamic (CFD) techniques. The 0D-1D model is applied to the first channel of the combustion chamber, subdivided in the following 4 control volumes (see **Figure 1**): i) RDF gasification control volume; ii) heat exchange volume placed upstream the gaseous combustion; iii) combustion of gaseous products; iv) heat exchange volume placed downstream the gaseous combustion region. The RDF gasification process is modelled assuming thermodynamic equilibrium, according to the following global reaction:



where $CH_xO_yN_z$ represents the equivalent chemical formula of the feedstock. Mass balance for carbon, hydrogen and oxygen are solved. Besides, thermodynamic equilibrium equation is solved for the Boudouard reaction, water-shift and methane oxidation [10]. Finally, the gasification temperature is calculated by solving the energy conservation equation, taking into account heat from reactions and radiation to the surrounding combustion chamber. The heat transferred between gaseous products and the working fluid (water vapour) is calculated using the heat exchangers equation, numerically estimating the global heat transfer coefficient, U ($Wm^{-2}K^{-1}$), on the basis of the characteristics of the solid walls of the combustion chamber. Finally, the combustion of gaseous products (control volume VC2) is considered, allowing the calculation of exhaust composition and of the heat power released.

The 3D detailed CFD model describes the pressure, velocity and temperature fields in the combustion chamber of the waste to energy plant by solving the well-known mass, momentum and energy conservation equations for compressible fluids. Turbulence is modelled using the Unsteady Reynolds Averaged Navier Stokes

(URANS) approach and the realizable $k - \epsilon$ turbulence model and final results are averaged over a sufficiently long time-interval of simulation. Boundary conditions for 3D simulations are obtained from simplified model results. In particular, gasification temperature and syngas mass flow rate are assumed in correspondence of the primary air inlet; the convective heat transfer coefficient, \bar{h} ($\text{Wm}^{-2}\text{K}^{-1}$), alongside with geometrical and thermophysical characteristic of solid walls of the combustion chamber (thickness and thermal conductivity of refractory bricks) are assumed in correspondence of non-adiabatic walls; temperature and mass flow rate mixture of secondary air and recirculating exhausts (if present) are assumed at the secondary air inlet sections. Besides, gaseous combustion process is modelled by imposing in the secondary air injection zone a proper heat source term, obtained from the simplified 0D-1D model. Convective heat transfer is calculated by performing additional simulations as a function of combustion chamber wall temperature. Finally, radiation is modelled by evaluating exhaust emissivity on the basis of composition obtained from simplified calculations. A schematic of the employed control volumes and the main interaction and between 0D-1D and 3D models are reported in **Figure 1**.

A schematic of the computational domain employed for simulations is available in Figure 2, where the air inlets and the exhaust outlet are indicated and the 3D reference system is highlighted in blue colour. In order to save computational resources, the computational domain was limited to the first radiant channel of the plant and only part of the second radiant channel, necessary to reproduce the passage area of the exhausts from the first to the second channel.

In **Figure 2** a picture of the adopted computational grid is also available, composed by 384773 points and tetrahedral 2068345 cells, chosen on the basis of a proper mesh grid independence analysis. The mesh is refined in correspondence of solid walls and secondary air inlets in order to properly capture local gradients. Finally, the grid presents a maximum non orthogonality of 61.5 with an average value of 14.7, while the maximum skewness factor is equal to 0.64.

Computational grid employed for simulations has been realized using the opensource software Salome®, while numerical simulations were performed employing the opensource code OpenFOAM®, based on the finite volume discretization approach [11].

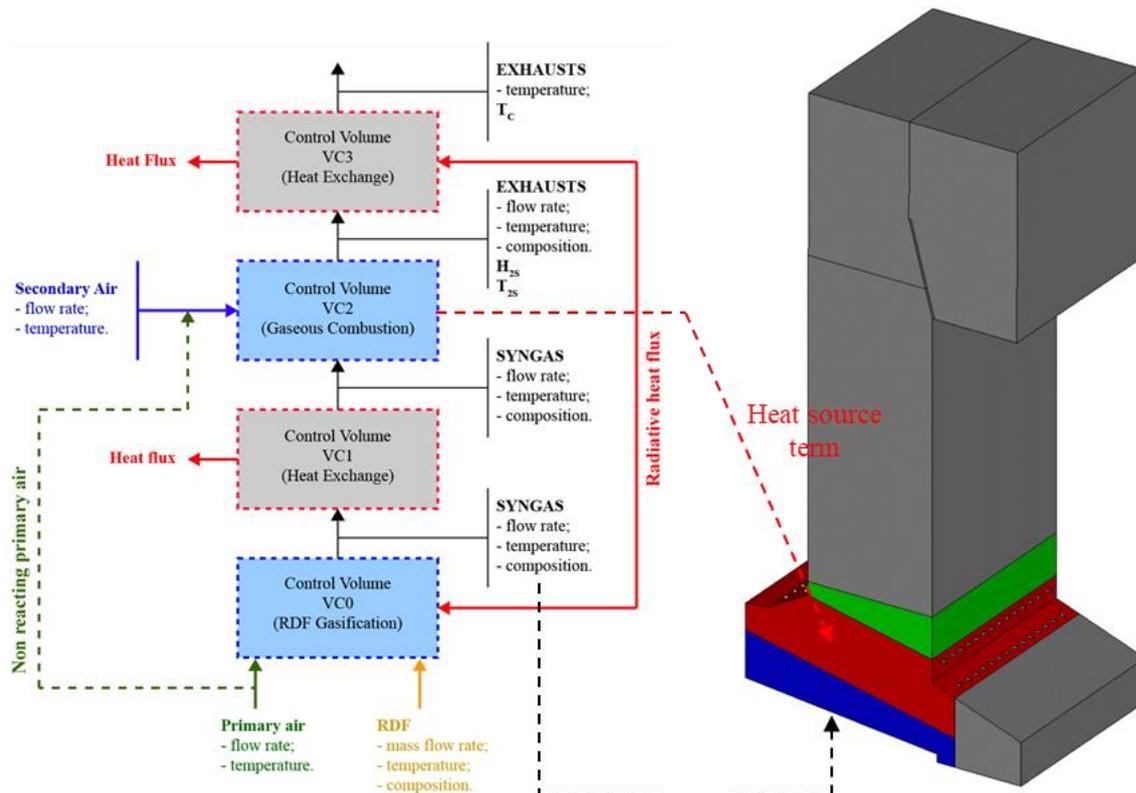


Figure 1. Schematic representation of the proposed general thermodynamic model.

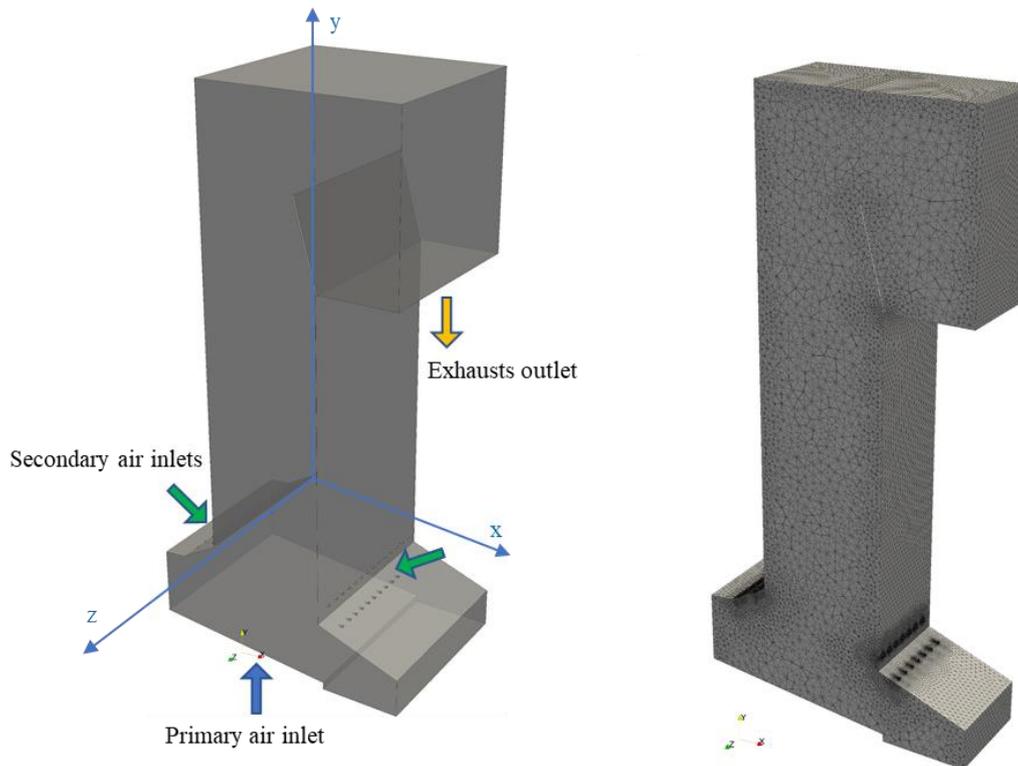


Figure 2. Computational domain (left) and computational grid employed for simulations (right) composed by 2068345 cells.

3. Results

The proposed 0D-3D numerical model was applied for the characterization of different operating conditions of an Italian WTE and in this paper the authors present the results obtained for only one operating condition, with the aim to demonstrate the effectiveness of the proposed numerical modelling approach.

Numerical simulations were performed reproducing the operating conditions of the plant in the reference period. For confidentiality constraint, results and data reported in this paper are normalized. In particular, the temperature has been normalized as a function of maximum temperature, T_{max} , and minimum temperature, T_{min} , obtained from calculations, according to the following equation:

$$T^* = \frac{T - T_{min}}{T_{max} - T_{min}} \quad (2)$$

Since simulations evidenced a periodic transient behaviour, the temperatures in equation (2) are obtained by averaging in time transient numerical results. Similarly, x, y and z coordinates are normalized with respect to length, width and height of the first vertical channel of the combustion chamber.

Figure 3 shows the streamlines (left) and the temperature field (right) obtained from numerical simulations. Streamlines are coloured on the basis of the value of the velocity module, even though no information about velocity range are here reported for confidentiality. From the analysis of **Figure 3** it can be immediately observed that the velocity field in the post-combustion chamber is fully three-dimensional, so clearly evidencing that the often employed assumption of 1D flow for the determination of the T_{25} temperature could be in practice unreliable. In fact, a large recirculating zone is observed at mid-height of the vertical channel, that is responsible of flow acceleration in correspondence of the front wall (maximum x value) of the first vertical channel of the post-combustion chamber. As a consequence, a non-uniform temperature is observed in correspondence of horizontal sections of the vertical channel, with larger temperature values in

correspondence front wall. As expected, largest temperature values in the domain are observed in the gaseous combustion sub-volume, where a heat source term is imposed for numerical simulations, while blue colour in such zone indicates lower temperature of the secondary air entering the computational domain.

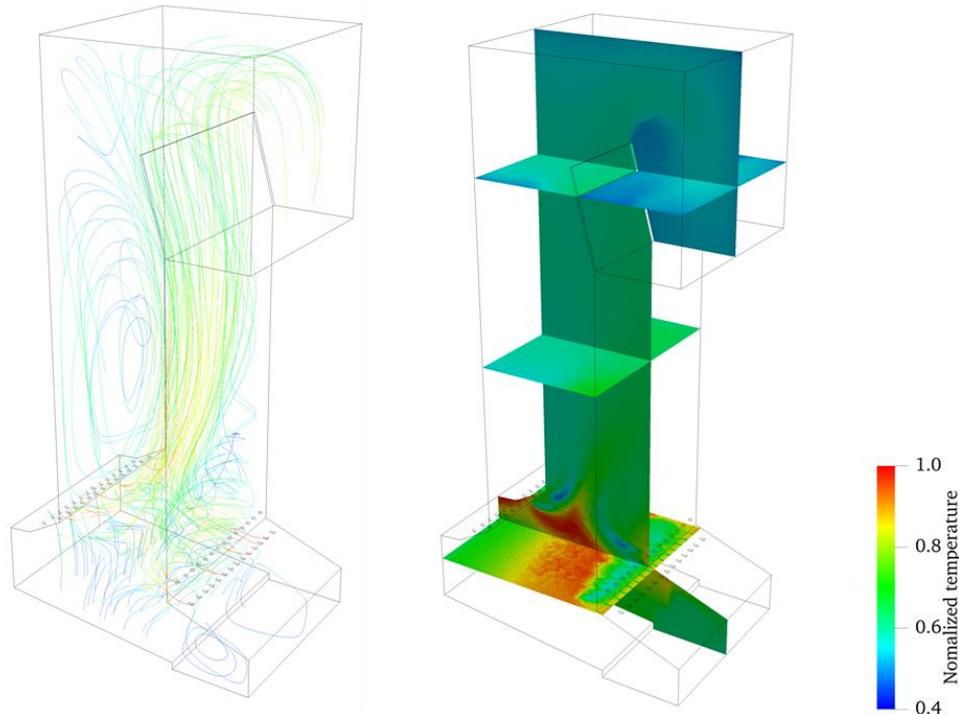


Figure 3. Streamlines (left) and normalized temperature field (right) obtained from numerical simulations.

Figure 4 shows the vertical normalized temperature profile numerically obtained in correspondence of the first vertical channel of the combustion chamber. The temperature value in correspondence of the smallest y^* value corresponds to the gasification temperature of solid RDF, obtained from the application of the 0D thermodynamic model and imposed as a Dirichlet boundary condition in correspondence of primary air inlet section for 3D CFD simulations. Temperature rise in the y^* region between -0.2 and 0 is due to gaseous combustion of syngas, while for $0.2 \leq y^* \leq 0.8$ the normalized temperature decreases very slowly. This is due to the presence of refractory material in correspondence of the internal walls of the first channel, whose objective consists of keeping the temperature above the value prescribed by current legislation for a sufficiently long period of time.

In order to validate numerical results, additional thermometers have been installed during WTE plant operation at a normalized height $y^* = 0.21$ and $y^* = 0.64$ at a normalized distance from internal wall $z^* = 0.07$. **Figure 5** shows the normalized temperature profiles numerically obtained in correspondence of the position of such thermometers, compared with measured normalized temperature. From the analysis of **Figure 5** it can be observed that the proposed numerical model is able to reliably reproduce actual operating condition of a WTE plant.

Numerical model has then been applied for the determination of the exhausts residence temperature in the combustion chamber after 2 second according to current legislation prescriptions, T_{2s} . To this aim a number of virtual sensors, representing discrete fluid particles, have been released in correspondence of last secondary air injection section, so allowing the determination of fluid particles position and temperature at different time values after the last combustion air injection, according to actual T_{2s} definition by European Legislation. **Figure 6** shows the results of such analysis for a resident time of 0s, 1.5s and 2.0s.

As expected, most of fluid particles move in the positive x direction and, after 2 s, are distributed along the whole height of the vertical channel. Such numerical approach allows the verification that no virtual sensors present a temperature lower than 850°C after 2 seconds, while the T_{2s} value is calculated as an average value of all released sensors in the combustion chamber after 2 seconds.

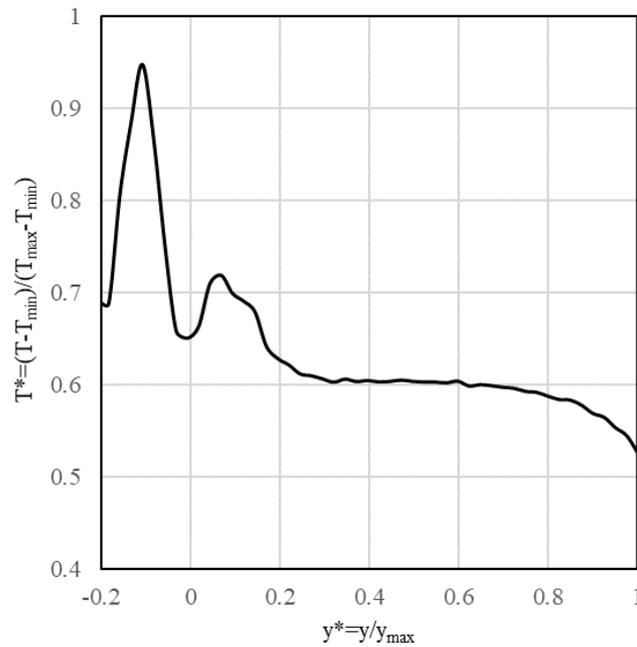


Figure 4. Vertical normalized temperature profile obtained from numerical simulation in correspondence of the first vertical channel of the combustion chamber.

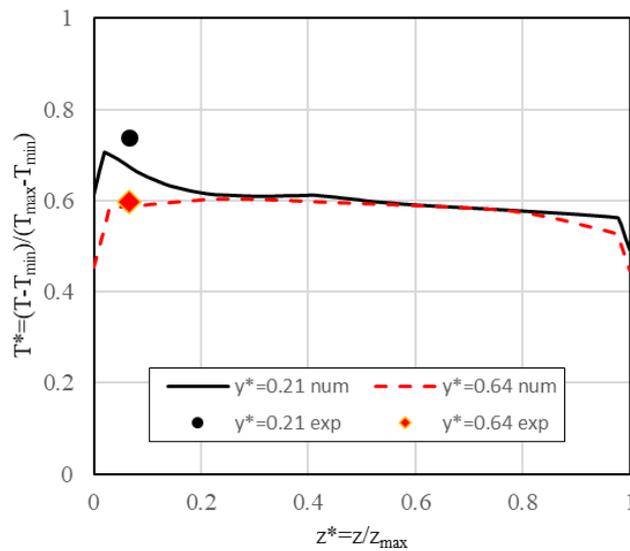


Figure 5. Horizontal normalized temperature profiles obtained in correspondence of a normalized height of $z^*=0.21$ and $z^*=0.64$ in the post-combustion chamber.

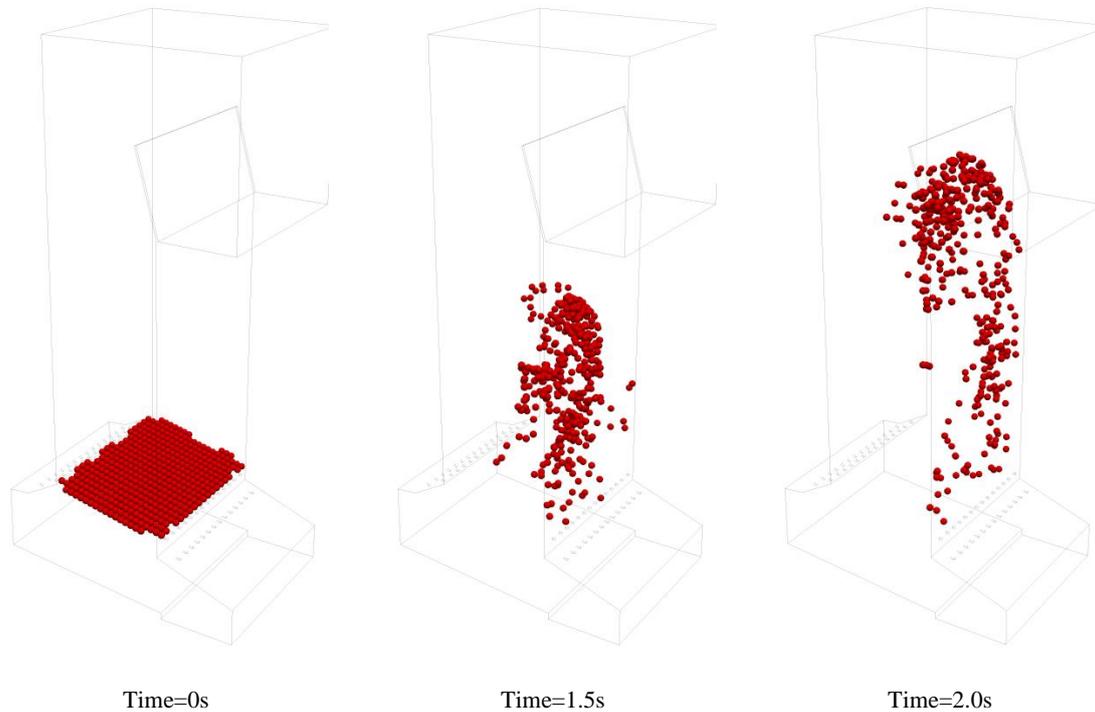


Figure 6. Fluid particles positions calculated form numerical simulations for the determination of the T_{2s} temperature.

The calculated value of the T_{2s} is not reported in this paper for confidentiality clause, but it is worth to evidence that analysed WTE plant fully satisfy the current legislation requirements for all the investigated operating conditions.

4. Conclusions

In this paper the authors propose a general 0D-3D model for the description of waste-to-energy (WTE) plants fed by RDF. An innovative methodology is proposed, combining a thermodynamic 0D parameters model, able to describe the processes of solid and gaseous combustion and the heat transfer within the first radiant channel, with a detailed 3D CFD simulation of the thermo-fluid-dynamic field within the plant combustion chamber. The proposed 0D-3D numerical model was applied for the characterization of different operating conditions of an Italian WTE and in this paper the authors presented the results obtained for one day-averaged operating condition. Numerical simulations were performed reproducing the operating conditions of the plant in the reference period. For confidentiality constraint, results and data reported in this paper are normalized. Additional thermometers were installed at different heights of the vertical channel of the combustion chamber during operation and obtained numerical results were compared with experiments showing a good agreement. The aim of the present paper is to demonstrate the effectiveness of the proposed numerical approach, as 0D-1D model allows the detailed description of solid gasification and gaseous combustion process, while three dimensional CFD simulations allow the prediction of T_{2s} temperature taking into account actual 3D characteristic of the flow. In fact, the comparison of results with detailed CFD simulations showed that the model presents a good reliability and flexibility, with the ability to calculate the T_{2s} temperature according to actual definition of European Legislation.

5. References

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