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The use of CFD for the prediction of problem areas inside a waste incinerator with regard to slagging, fouling and corrosion.

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ABSTRACT

The physical and chemical operations, which are proceeding on the grate and in the furnace are: drying, pyrolysis, gasification, heterogeneous combustion and burnout of the waste and the turbulent combustion of the gaseous species.

Problems occurring in several incinerators are caused by slagging, fouling and corrosion. For example the build-up of slag around the secondary air nozzles is a major problem in the operation of incinerators. HCl-CO-corrosion mechanisms are driven by CO and HCl-concentrations in the boundary layers of the furnace walls.

The mixing of the secondary air in the furnace is the most important feature to reach uniform oxygen, temperature and velocity distributions to reduce the danger of the above phenomena.

At the Institute of Environmental Process Engineering and Plant Design (Lehrstuhl für Umweltverfahrenstechnik und Anlagentechnik, LUAT) simple mathematical submodels were developed for the description of the heterogeneous combustion of the solid waste. The thermal input is defined as the integral of the function “generation of heat“ over the grate. The heat release profile along the grade is a function of the axial distance of the waste input and the partition of volatile matter in relation to the sensitive heat at the waste surface. Volatiles emitted from the waste surface are CO and C_xH_y. The gas products CO_2, CO, H_2O and C_xH_y released from the packed bed are calculated in the same way as the heat release. The concentrations of the oxygen are described by an opposite profile over the grate.

Gas phase simulations in combination with particle trackings were performed in the complete threedimensional furnace and burnout chamber respectively the radiational part of a model-MSW incinerator for several cases and furnace geometries with the FLUENT®-CFD-Code. Near the furnace walls and the secondary air nozzles a higher grid resolution was chosen to investigate local temperature and concentration peaks. An optimization of the incinerator could be achieved by variation of the secondary air injections and the furnace geometry.

KEYWORDS

Waste Incinerator, Mathematical Modelling, Corrosion/Slagging/Fouling, Furnace Geometry, CFD

INTRODUCTION

To burn refuse is much more difficult than normal fossil fuels and the risk of slagging, fouling, erosion and corrosion is relatively high.

Slagging deposition is caused by particles hitting the walls at temperatures above the sticking point. The depositions influence the heat transfer to the walls, the operation of the secondary air nozzles and therefore the whole combustion process. Corrosion is a major problem in boiler plants, especially in those burning or incinerating waste fuels. The varying composition of the fuel and the high content of aggressive gaseous compounds seem to be the essential factor for the problem. To a great extent the lifetime of heat exchanger tubes in boilers depends on the rate of fireside corrosion. Corrosion is the chemical reaction of a material with components of the environment. It is known that corrosion rates are related to the chemical load (which is a function of fuel composition and burning conditions), the wall temperature, the flue gas temperature and the properties of the tube materials. Corrosion in the combustion chamber is often caused by local reducing conditions or chlorine compounds. Corrosion in the superheater area is normally caused by “high temperature chloride corrosion” [1-5].

There are two basic types of corrosion problems :

- high-temperature corrosion (can be subdivided in 3 corrosion mechanisms) :

  The first type is the liquid phase corrosion. It´s caused by molten alkali metal salts, for example metal chlorides and their eutectic mixtures which have very low melting points. The second basic high-temperature problem is corrosion due to chloride, usually above 475°C. The third problem is the non-uniform furnace atmosphere. Corrosion often occurs in reducing environments wherein carbon monoxide and hydrogen sulfide are produced (usually between 400 and 600°C). The gases react with the protective layer of iron oxide on the tubes, exposing them to a corrosive attack.

- low-temperature corrosion

  The low-temperature corrosion is a typical problem in any combustion plant burning fuels containing sulphur and chlorine. Sulphur trioxide combines with water vapor to form sulphuric acid which are below the acid dew point. Carbon dioxide could combine with water vapor to from carbonic acid, which is a weak acid. This corrosion is just relevant at the “cold end” of a plant.

MATHEMATICAL MODEL FOR THE GASEOUS PHASE

Numerical modelling of industrial burners has been the subject of several studies. Simulations of pulverized coal or gas flames were made worldwide since about 20 years [e.g. 6-8]. Relatively little work has been published on MSW incinerators [9–15] because of the complicated description of the physical and chemical operations. In contrast to pulverized coal the waste composition isn´t constant.

For a general field quantity φ the instantaneous transport equation can be written in the form :

$$\frac{\partial}{\partial t}(\rho\,\varphi) + \frac{\partial}{\partial x_j}(\rho\,\varphi\,u_j) = \frac{\partial}{\partial x_j}\left(D_\varphi \frac{\partial \varphi}{\partial x_j}\right) + S_\varphi \qquad (1)$$

where : $\frac{\partial}{\partial t}(\rho\,\varphi)$ is the transient term, $\frac{\partial}{\partial x_j}(\rho\,\varphi\,u_j)$ is the convection term,

$\frac{\partial}{\partial x_j}\left(D_\varphi \frac{\partial \varphi}{\partial x_j}\right)$ is the diffusion term, S_φ is the source term

and : t = time, ρ = density, u = velocity components, x = distance, j = coordinate direction

A generally accepted method to approximate the turbulence in flows is the time-averaging (Reynolds averaging) of the instantaneous transport equation. A turbulence model is required for the unknown correlations of the fluctuating velocity components (Reynolds stresses $\rho \bar{u}'_j \bar{u}'_j$). Very often the standard k-ε-model (requires the solution of two additional transport equations, those for the kinetic energy of turbulence, k, and its dissipation rate ε) is used for the turbulence closure. FLUENT´s P-1-radiation model (six flux method) was used to calculate the source term in the enthalpy balance equation where φ is substituted by the enthalpy h. For each of the chemical species, except N_2, a mass conservation equation is solved for the mass fraction. A two step reaction mechanism has been modelled as follows :

- $CH_4 + 1{,}5\ O_2 \rightarrow CO + 2\ H_2O$ and
- $2\ CO + O_2 \rightarrow 2\ CO_2$

The various source and sink terms in the chemical species balance were calculated by using a modified eddy break up model based on the method of Magnussen and Hjertager [15]. Apart from the density, the chemical species mass fraction, the turbulent kinetic energy and the turbulent viscous dissipation rate, a proportionality constant, called the mixing rate coefficient A_{mix}, appears in the combustion rate expression. Magnussen proposes $A_{mix} = 4$ [17], in these simulations a value of 0.6, based on several studies at the IFRF [18-19], was used.

INCINERATOR MODEL

At the Institute of Environmental Process Engineering and Plant Design (LUAT) simple mathematical submodels were developed for the heterogeneous combustion of the solid waste. Several successful simulations, optimizations and investigations were made at the LUAT in the last 2 years. The model was validated and the difference between the experimental and predicted data was very satisfied [9, 14, 15]. The thermal input is defined as the integral of the function “generation of heat“ over the grate (figures 1 a+b).

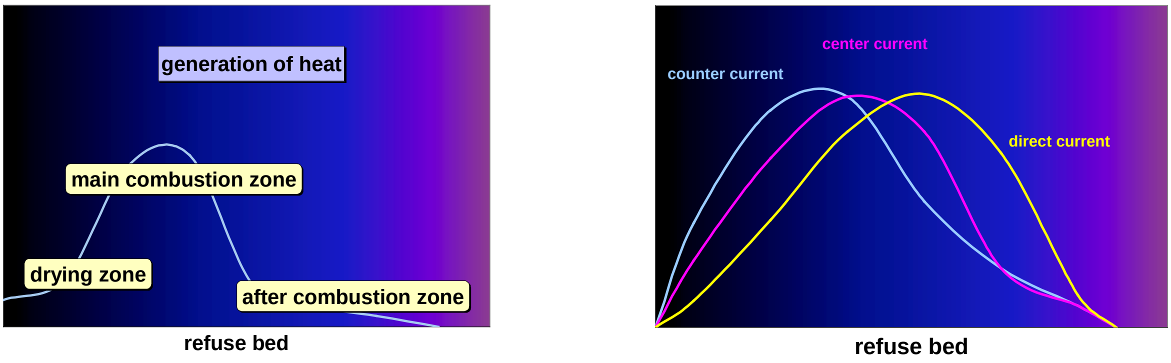


Figure 1 : a) Heat release over the grate (outline)
b) Heat release profiles depending on the plant design (Furnace geometry)

The temperature profile has the same form and is calculated as follows :

$$T = \frac{\dot{H}_{sensible}}{c_p \; \dot{m}_{gas}} \qquad (2)$$

$$\text{where} \quad \dot{H}_{sensible} = \dot{Q}_{in} - \dot{H}_{latent} = \dot{m}_{waste} \cdot LCV_{waste} - \dot{H}_{latent} \qquad (3)$$

$$\text{and} \quad \dot{H}_{latent} = (LCV_{CxHy} \cdot \mu_{CxHy} + LCV_{CO} \cdot \mu_{CO})\; \dot{m}_{gas} \qquad (4)$$

$$\text{with}: \dot{m} = \text{mass flow}, \dot{Q} = \text{thermal input}, c_p = \text{specific heat}, \; \dot{H} = \text{enthalpy flow},$$
$$LCV = \text{lower calorafic value}, \mu = \text{mass fraction},$$

The ratio between sensible and latent heat enthalpy is determined by a species distribution assumption. For this study it was assumed that C and H reacts to CO_2, CO, CH_4 and H_2O. The gaseous products CO_2, CO, H_2O and C_xH_y releasing from the packed bed are calculated in the same integral way as the heat release. The concentrations of O_2 are described by an opposite profile over the grate. More detailed description about the model can be found f. e. in [15].

DESCRIPTION OF THE MSW INCINERATOR PLANT

3 furnace geometries (parallel flow, counter flow and center flow) were investigated and are presented in figure 2. Because of a symmetry only one half with a width of 3 m was modelled (BFC with up to 350.000 cells). For the refractory material “Refrax70” and chosen heat fluxes wall temperatures were calculated in the combustion chamber and in the first path.

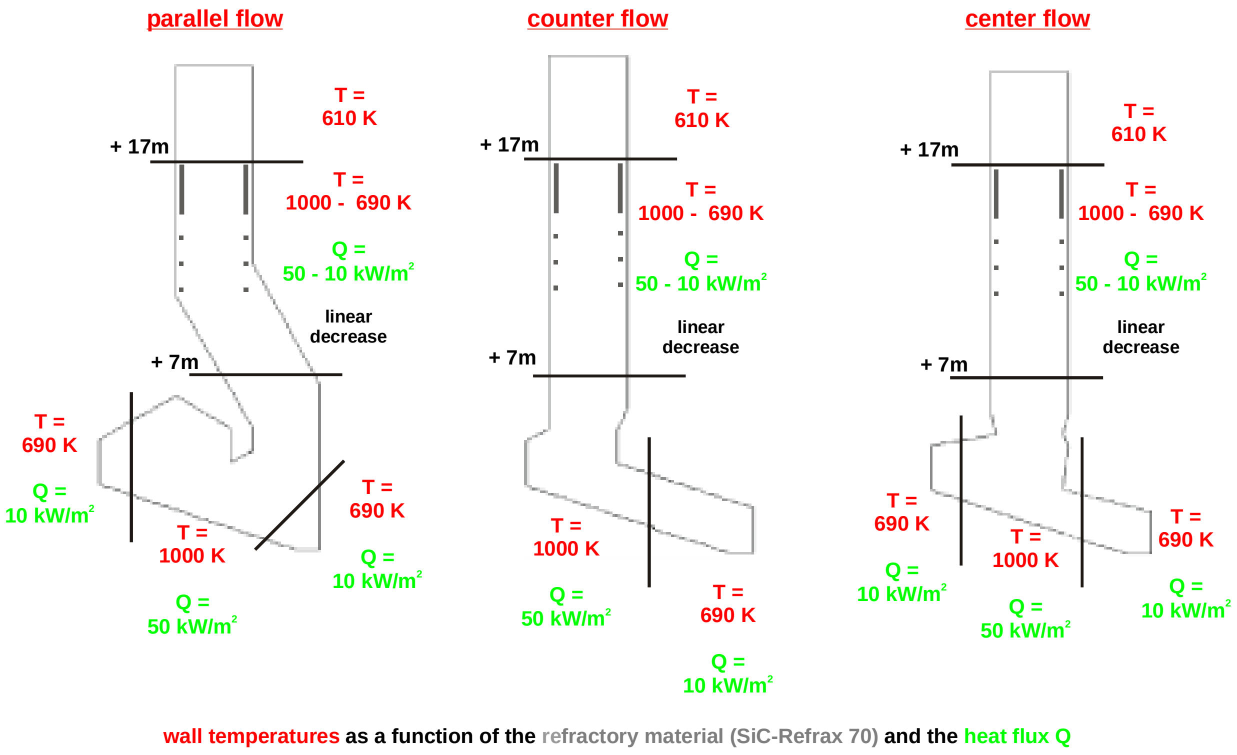


Figure 2 : Incinerator geometries (parallel flow, counter flow + center flow)

The secondary air distributions for all cases are displayed in fig. 3. Other boundary conditions and process variables are listed in table 1. For the incinerator geometry "center flow" also a displacement body was investigated. Good results which such a displacement body were made f.e. in the MSW-plant of Bonn (Germany) with the so called IBB-Bonn-Prism [14-16, 20].

primary air flow [m^3/h]	secondary air flow [m^3/h]	waste through put [t/h]	LCV of waste [MJ/kg]	composition of the waste (mean values)				
				c [kg/kg]	h [kg/kg]	o [kg/kg]	ash [kg/kg]	water [kg/kg]
70.000	**21.000**	**15**	**10**	**0.27**	**0.03**	**0.17**	**0.26**	**0.27**

Table 1 : Waste compositions, process variables and boundary conditions

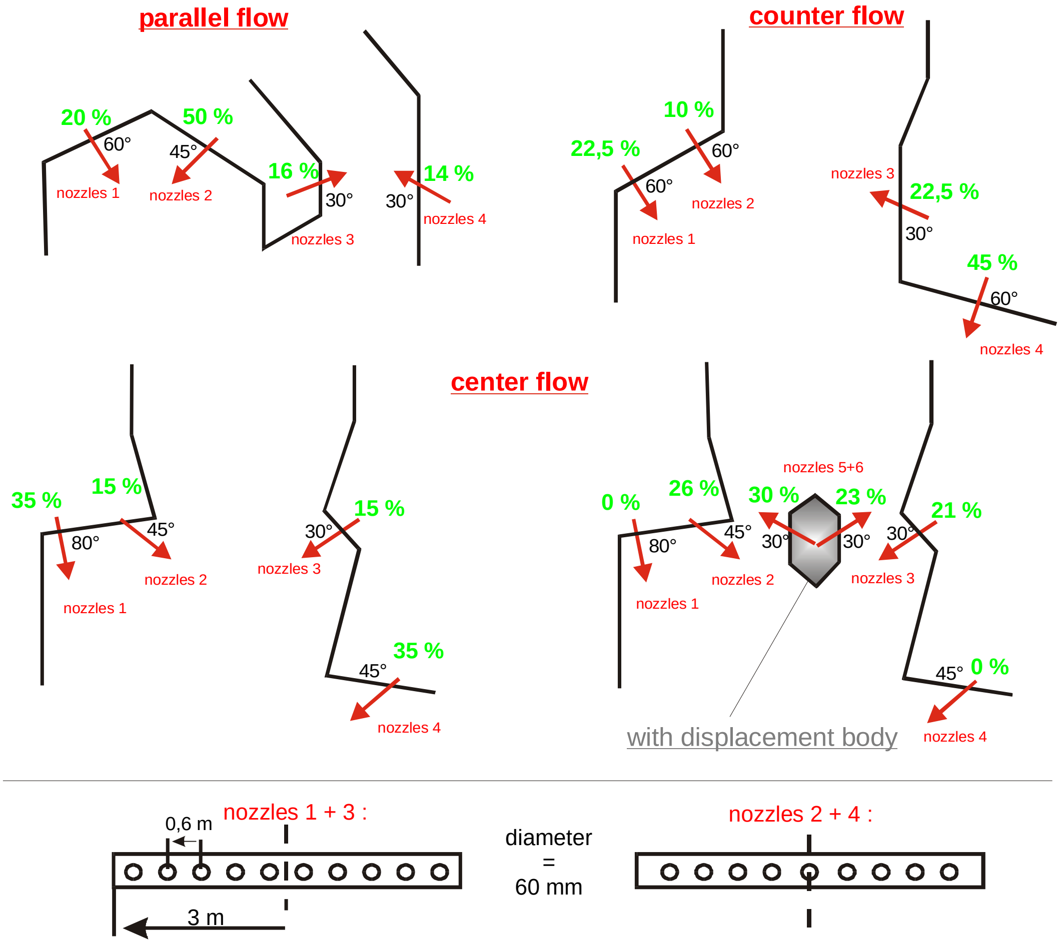


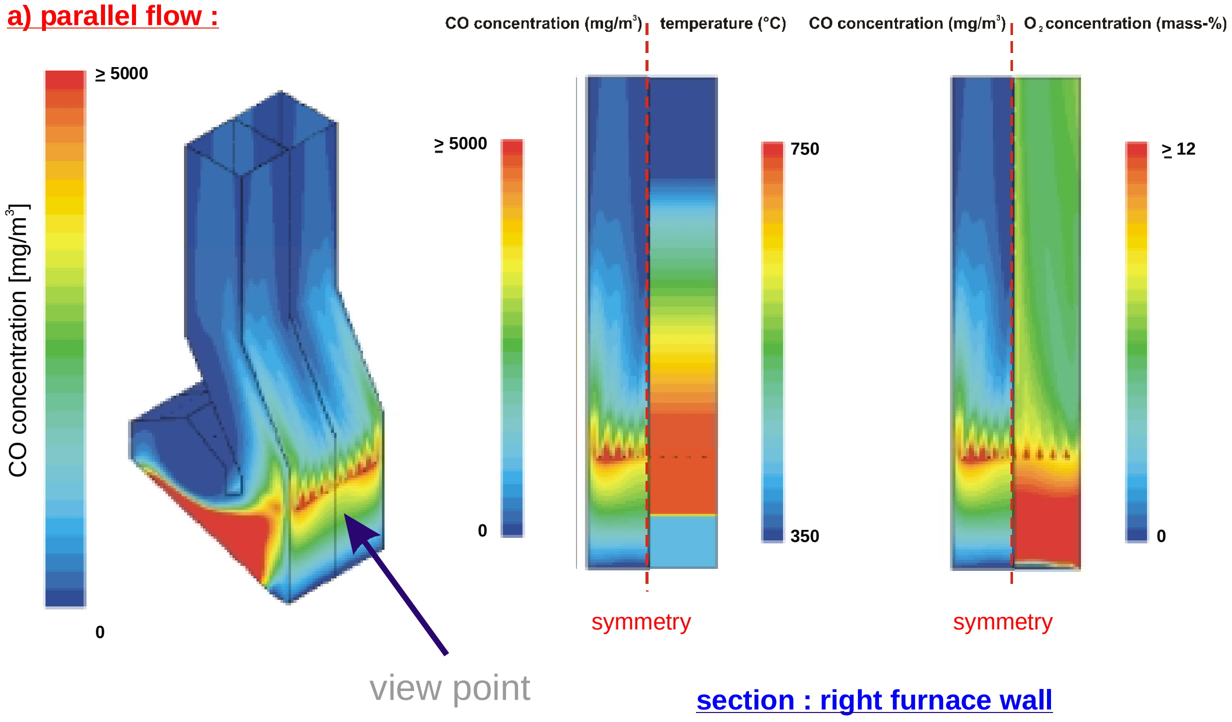
Figure 3 : Secondary air distributions

RESULTS

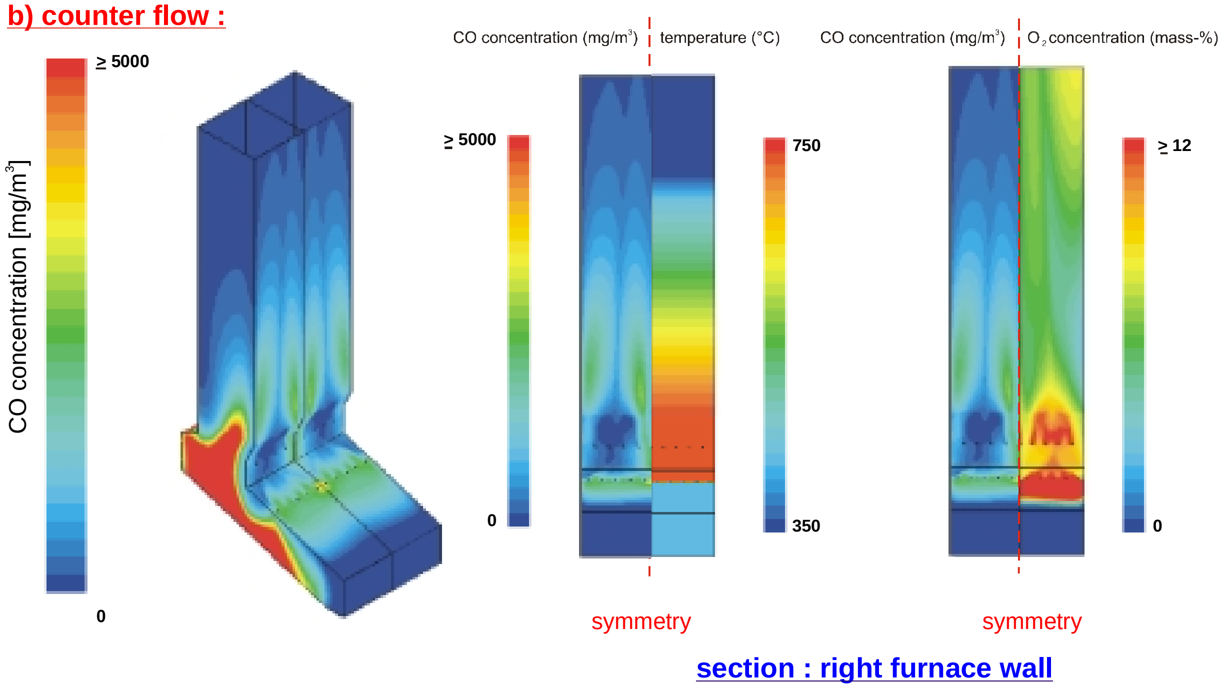
The problem areas with regard to corrosion can be analysed by the CO distribution. Reducing environments with local high CO concentrations and low oxygen concentrations could cause CO corrosion. The CO, O_2 and temperature distributions near the walls (distance : mm – cm) are presented for the 4 cases in figure 4.

CO, O_2 and temperature distributions near the walls

a) parallel flow :

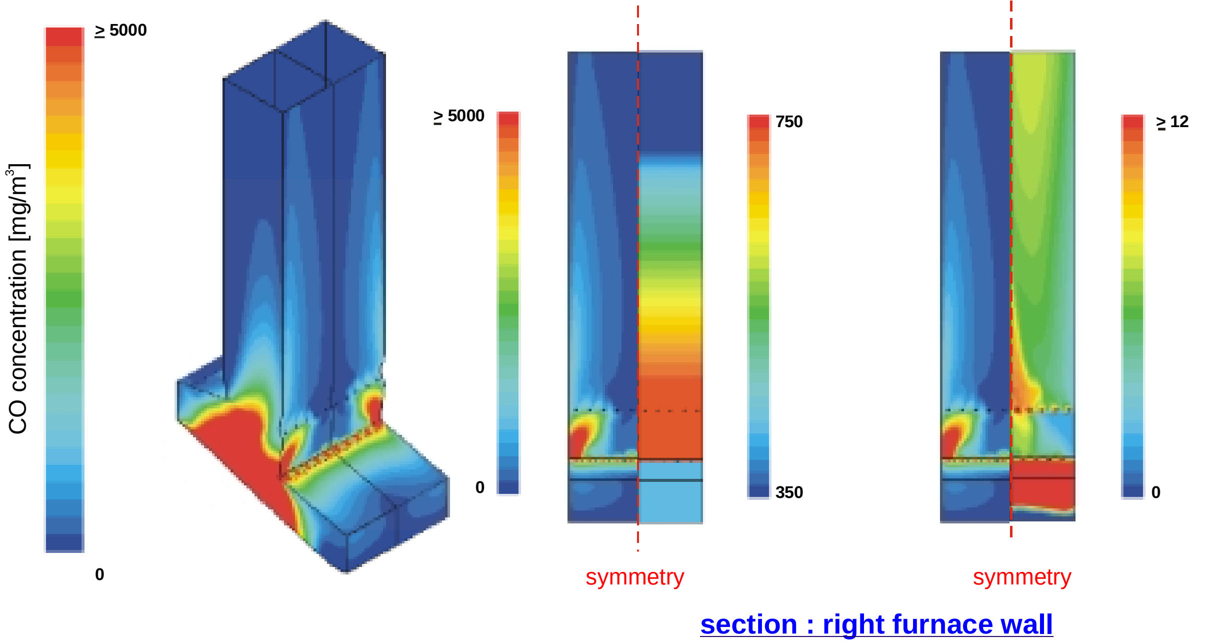


b) counter flow :

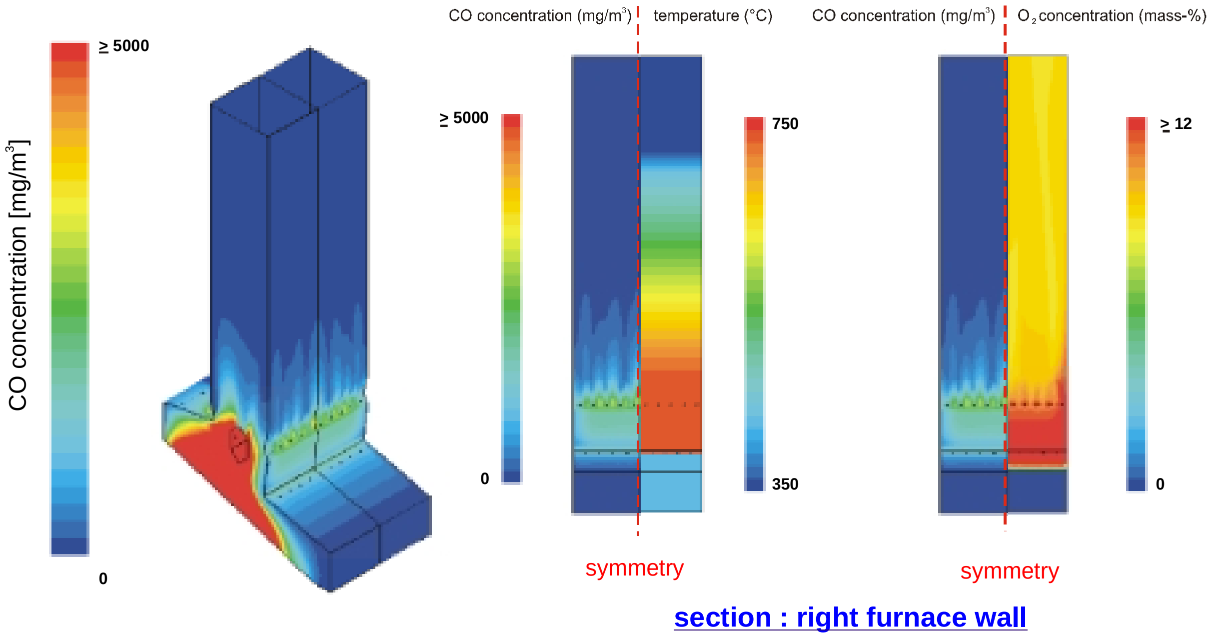


Figures 4 : The CO, O_2 and temperature distributions near the walls
a) parallel flow b) counter flow

c) center flow :



d) center flow (with displacement body) :



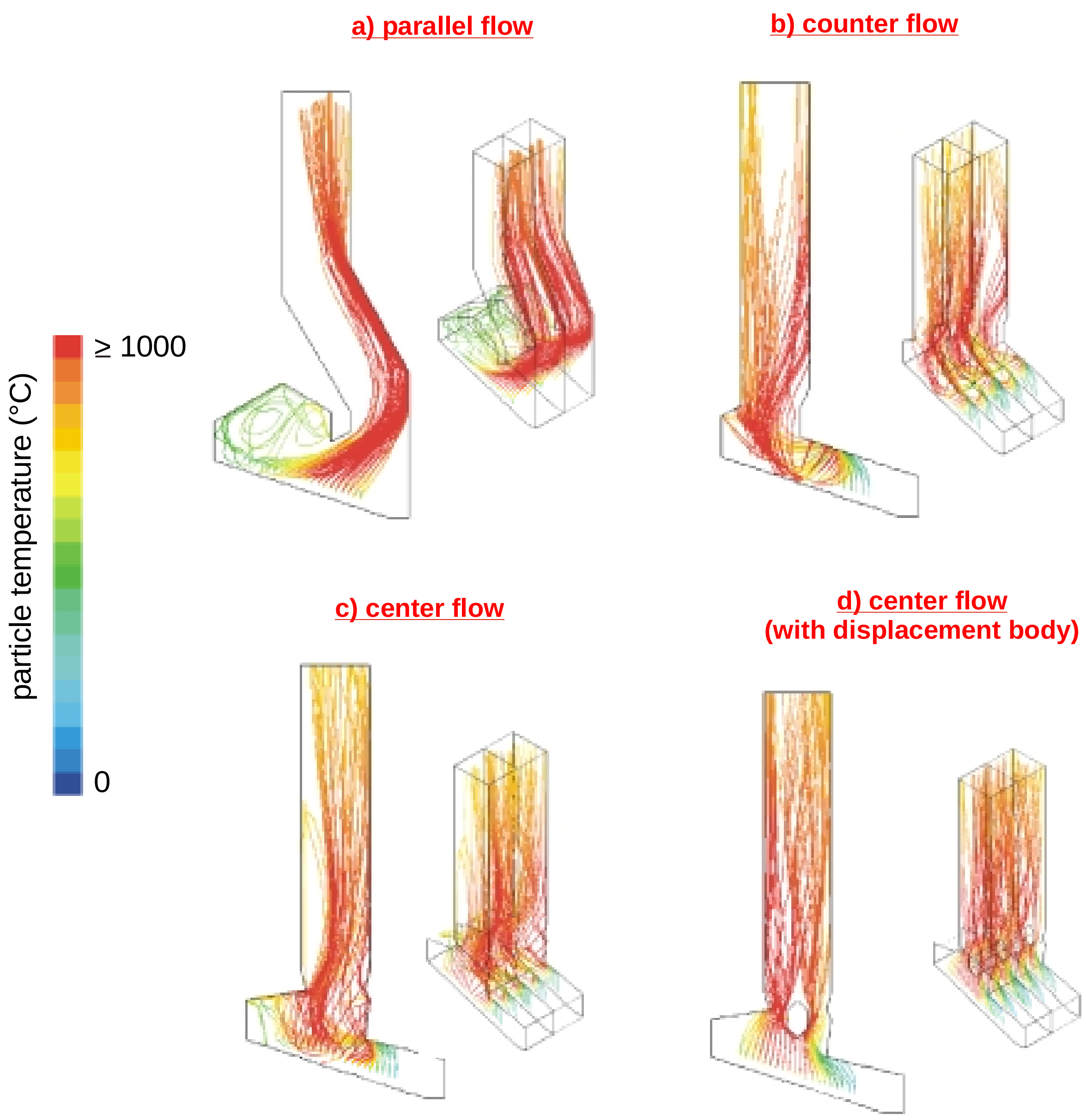
Figures 4 : The CO, O_2 and temperature distributions near the walls
c) center flow d) center flow with displacement body

In the figures 4 a-c) high CO concentrations can be detected at some local areas near the wall. For the case “parallel flow” concentrations over 5000 mg/m^3 were predicted between the secondary nozzles “4”. The main flow with high amounts of CO bounds against the right furnace wall and except of the air nozzles very high concentrations of carbon monoxide can be found therefore at these regions. Besides a secondary flow in the width cause a heterogeneous combustion and an incomplete burnout. For the cases “counter flow” and “center flow” the maximum CO concentration at the outlet is lower by a factor of about 5 in relation to the “direct flow”. This indicates that the combustion process in total is much better, but in both cases secondary flows also exist, therefore local high carbon monoxide concentrations can be found as well near the walls. The oxygen concentrations are very low at some places, with an amount of about 2,5 mass-% for “counter flow” and 5 mass-% for “center flow”. A very good combustion process was predicted for the “center flow” with use of a displacement body. With the displacement body the width of the path at the end of the main combustion chamber is reduced considerably. The whole cross section is full covered by the secondary air jets, which leads to a good mixing between the pyrolysis gases and the secondary air and to uniform temperature, velocity and species (e.g. the O_2 distribution in figure 4d : the concentration in the whole first path is nearly constant). With the use of this displacement body the maximum CO concentration at the end of the first path could decrease again from over 300 mg/m^3 (center and counter flow) to values lower than 150 mg/m^3. CO corrosion often occurs between 400 and 600°C. For all cases and the chosen refractory material these temperatures can be found near the walls and therefore the possibility of CO corrosion is given.

The critical zones for slagging, erosion and fouling can be demonstrated by particle tracks. After the gaseous phase simulations trajectories were computed using a Lagrangian formulation and the inert heating model [21]. The trajectories of the dispersed phase particles are predicted by integrating the force balance on the particle. Particle tracks which were predicted using the mean fluid phase velocity are presented for the 4 cases in figures 5.

The sticking point of the particles were defined as 1000°C which indicates the “best case” because some melting points, especially for eutecticas, are far below 1000°C. The right side of the first path is the problem area for the case “direct flow” (figure 5a). The main flow bounds against the right furnace wall and therefore a high amount of particles can be found at these areas which can cause erosion and slagging. The flow field for the cases “counter flow” and “center flow” (figures 5b and c) is much better, but not satisfied. Nearly at all places in the first path particles can be recognised for both designs, but there are also some heterogeneous zone. In the “counter flow” a part of the main flow with particles over 1000°C isn´t parallel to the first path, but shows a direction to the right wall which can lead to slagging. Particle temperatures about 1000°C are also present near the secondary air nozzles “4”. If slagging occurs in these regions, the air jets will be influenced by the slag (for example : diameter and angle). The flow field in the “center flow” looks better, but on the left side a recirculation zone can be observed where a lot of particles can concentrate and cause fouling. A very uniform flow field was predicted for the “center flow” with use of a displacement body (figure 5d). No recirculation zone and a main flow parallel to the furnace walls were calculated. The whole section is covered by the particles and no local high particle concentrations are recognised. Therefore the risk of slagging, erosion and fouling is very low in contrast to the other cases.

Particle tracks (d_p = 0.1 - 1 mm, mean tracks)



Figures 5 : Mean particle tracks (d_p = 0.1 – 1 mm, 3 x 20 start points over the grate)
a) parallel flow b) counter flow
c) center flow d) center flow with displacement body

CONCLUSION

This study has demonstrated that CFD simulations can be used for a prediction of problem areas regarding to corrosion, erosion, slagging and fouling inside an incinerator. Only a tendency can be observed, but as the 4 cases have shown, CFD is a very good tool to see what happens at every place inside the waste incinerator. The distributions for the cases “counter flow” and “center flow” looked much better and more uniform as for “direct flow” which means that a better combustion process can be achieved only by another design. The best distributions were predicted for the “center flow” in combination with a displacement body. Good results which such a displacement body were performed in Bonn and it could confirm again by these investigations. A very uniform flow field leads to nearly constant oxygen values in the whole first path. No local high amounts of CO or particles could be observed and therefore the risk of corrosion, erosion, slagging and fouling is relatively low.

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