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Numerical Calculation and Optimisation of a large Municipal Solid Waste Incinerator Plant

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Numerical calculation and optimisation of a large municipal solid waste incinerator plant

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ABSTRACT

Incineration of municipal waste is one of the most complex unit processes presently in use. An optimisation in the emissions, specially of NO_x, is possible by a separate addition of the combustion air via primary and secondary air. The mixing of the secondary air in the furnace is the most important feature to reach uniform oxygen, temperature and velocity distributions.
The description of the physical and chemical operations, which are proceeding on the grate and in the furnace (e.g. the heterogeneous combustion of the solid waste, the drying of the waste or the turbulent combustion of the gas species) are very complicated because of the large range of the waste composition.
At the Institute of Environmental Process Engineering and Plant Design (Lehrstuhl für Umweltverfahrenstechnik und Anlagentechnik, LUAT) simple mathematical submodels were developed for 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 releasing from the packed bed are calculated in the same way as the heat generation. The concentrations of the oxygen are described by an opposite profile over the grate.
Three-dimensional gaseous phase simulations with FLUENT® were made in a complete furnace and burnout chamber respectively the radiational part of a large MSW incinerator for several cases. Temperature, species and velocity distributions could be improved by a so called „Prism" [1]. That´s an additional secondary injection port between the furnace and the first path.
For special conditions measured data were available at different control sections (grid measurements) and could compared to the simulation results. The difference between the simulated and experimental data was very low for the reference case.

INTRODUCTION

The quantity of household, industrial and domestic waste has increased steadily in the last years. A major part is treated in a thermal process. The two main advantages of incineration are :

- large volume reduction and
- recovery of energy to generate electricity / steam.

To minimise the pollutants from MSW incinerators legal requirements were introduced in several countries [2-4]. The directives specify a gas residence time of 2 seconds at temperatures of not less than 850°C to ensure the destruction of organic compounds.
Incomplete products of combustion can be reduced by the 3 T´s :

- temperature,
- time and
- turbulence.

Most incinerators employ an inclined moving grate where the waste is dried, devolatilized and burned using primary air. To effect complete combustion high velocity secondary air jets are used. Previous studies have shown the importance of the secondary air injection [5-7]. But there are a lot of design variables which can improve or deteriorate the efficiency of mixing :

- secondary air distribution,
- number of the nozzle arrays,
- location of the nozzle arrays and
- injection angle of the nozzles,
- number of nozzles,
- diameter of nozzles.

Apart from the secondary air injection many other design variables exist :

- furnace geometry,
- type of grate,
- grate movement,
- refuse bed.
- primary air distribution,
- ratio primary/secondary air,
- excess air and

The high amount of design variables listed above strongly suggests that present designs and mode of operation are far from optimum.
The purpose of this study was to investigate the effect of the additional secondary air nozzles placed in the „Prism" and to optimise the design variables of the secondary air injection (angle, diameter, location, ...) by numerical flow simulations.

MATHEMATICAL MODEL FOR THE GASEOUS PHASE

Numerical modelling of industrial burners has been the subject of several studies. Simulations of pulverised coal or gas flames were made world-wide since about 20 years [e.g. 8-10]. Relatively little work has been published on MSW incinerators [11-14] because of the complicated description of the physical and chemical operations. In contrast to pulverised 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

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 $\rho\, \overline{u'_j}\, \overline{u'_j}$). 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.

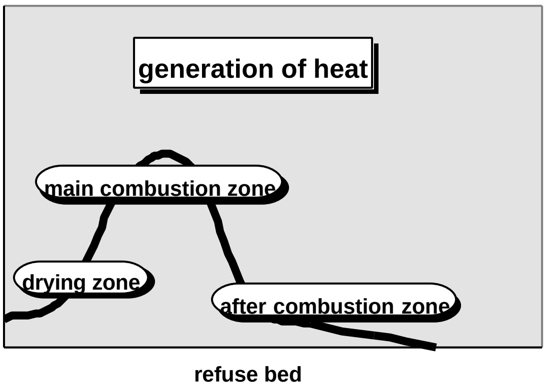
For each of the chemical species, except N_2, a mass conservation equation is solved for the mass fraction. A two step reaction mechanism has been modelled as follows :

- $CH_4 + 1{,}5\ O_2 \rightarrow CO + 2\ H_2O$ 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]. The reaction rate was computed from Arrhenius rate expressions and by using the eddy dissipation concept. The limiting (slowest) rate was used as the reaction rate and the contribution to the source terms in the species conservation equations are calculated from this reaction rate.
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 $A_{mix} = 4$ [16], in these simulations a value of 0.6, based on several studies at the IFRF [17-18], was used.

INCINERATOR MODEL

At the Institute of Environmental Process Engineering and Plant Design simple mathematical submodels were developed for the heterogeneous combustion of the solid waste. The thermal input is defined as the integral of the function “generation of heat“ over the grate (figure 1).



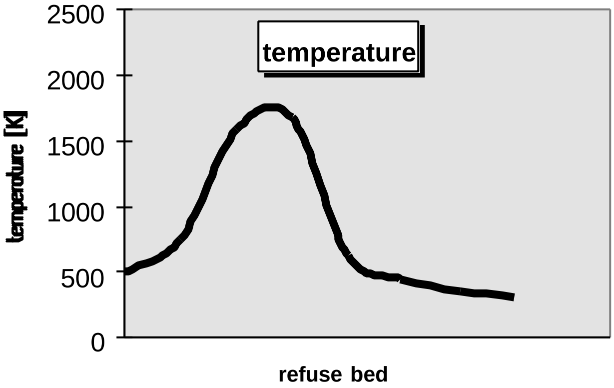


Figure 1 : Generation of heat over the grate   Figure 2 : Temperature profile over the grate

The temperature profile has the same form (figure 2) and is calculated as follows :

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

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

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

The ratio between sensible and latent heat is determined by a species distribution assumption. For this study we assumed that C and H reacts to CO_2, CO, CH_4 and H_2O. The distribution shows fig.3.

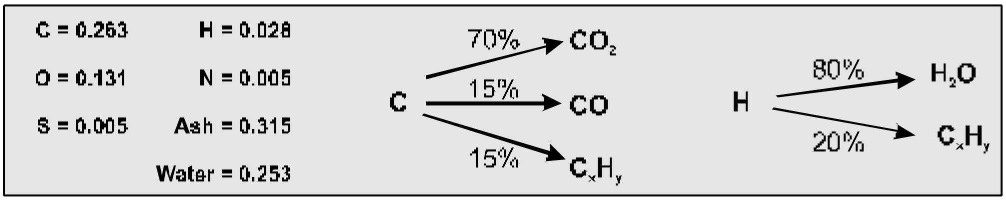
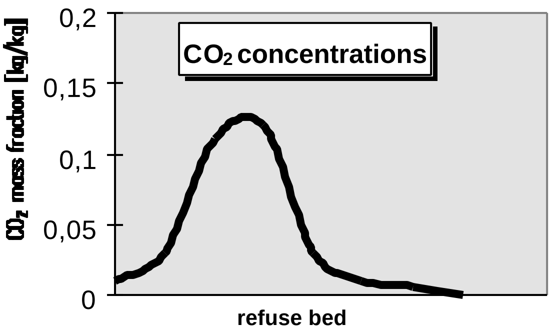


Figure 3 : mean waste composition and distribution assumption for c and h

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 generation. The concentrations of the oxygen are described by an opposite profile over the grate. Figures 4 and 5 show the CO_2 and O_2 profiles over the waste layer.



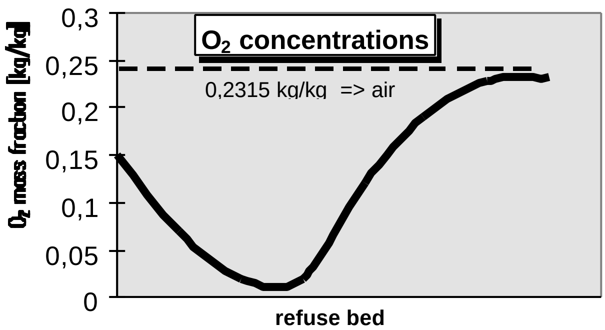


Figure 4 : CO_2 concentrations over the waste layer   Figure 5 : O_2 profile over the grate

DESCRIPTION OF THE MSW INCINERATOR PLANT

The geometry of the furnace is presented in figure 6. Grid measurements were made at 12 special points in 2 measurement planes. Because of a symmetry only one half with a width of 2.6 m was modelled (BFC with 53 x 52 x 61 = 168116 cells). Calculations were performed using a SGI-Indigo^2. For one case approximately 24 hours of cpu time (≈ 1500 iterations with 1 iter./min) were required. The simulation show the advantages of the „Prism“ :

- complete burnout in the flue gas (partial direct current flow)
- CO minimisation and constant oxygen concentrations in the flue gas (reduction of corrosion)

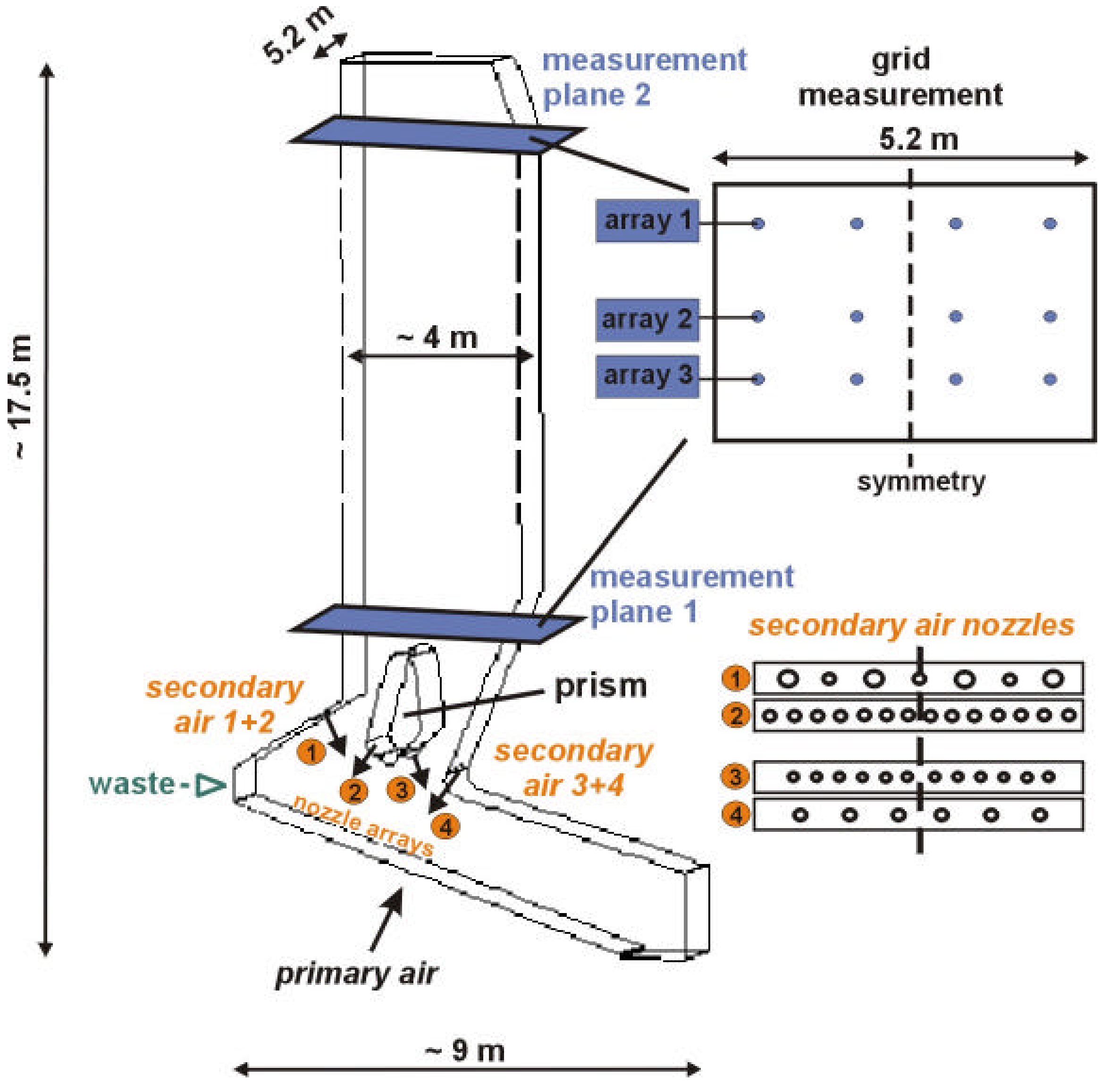
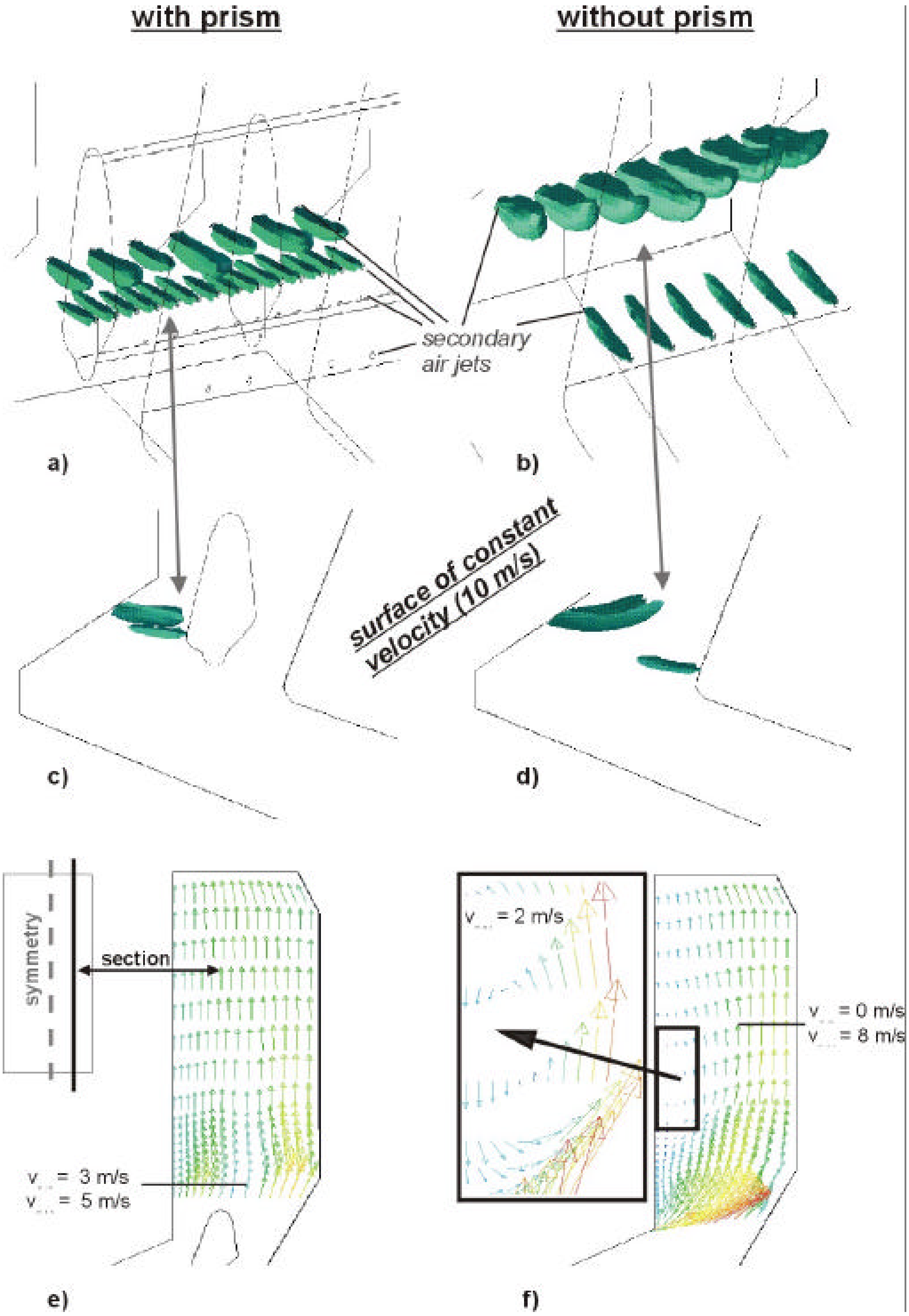


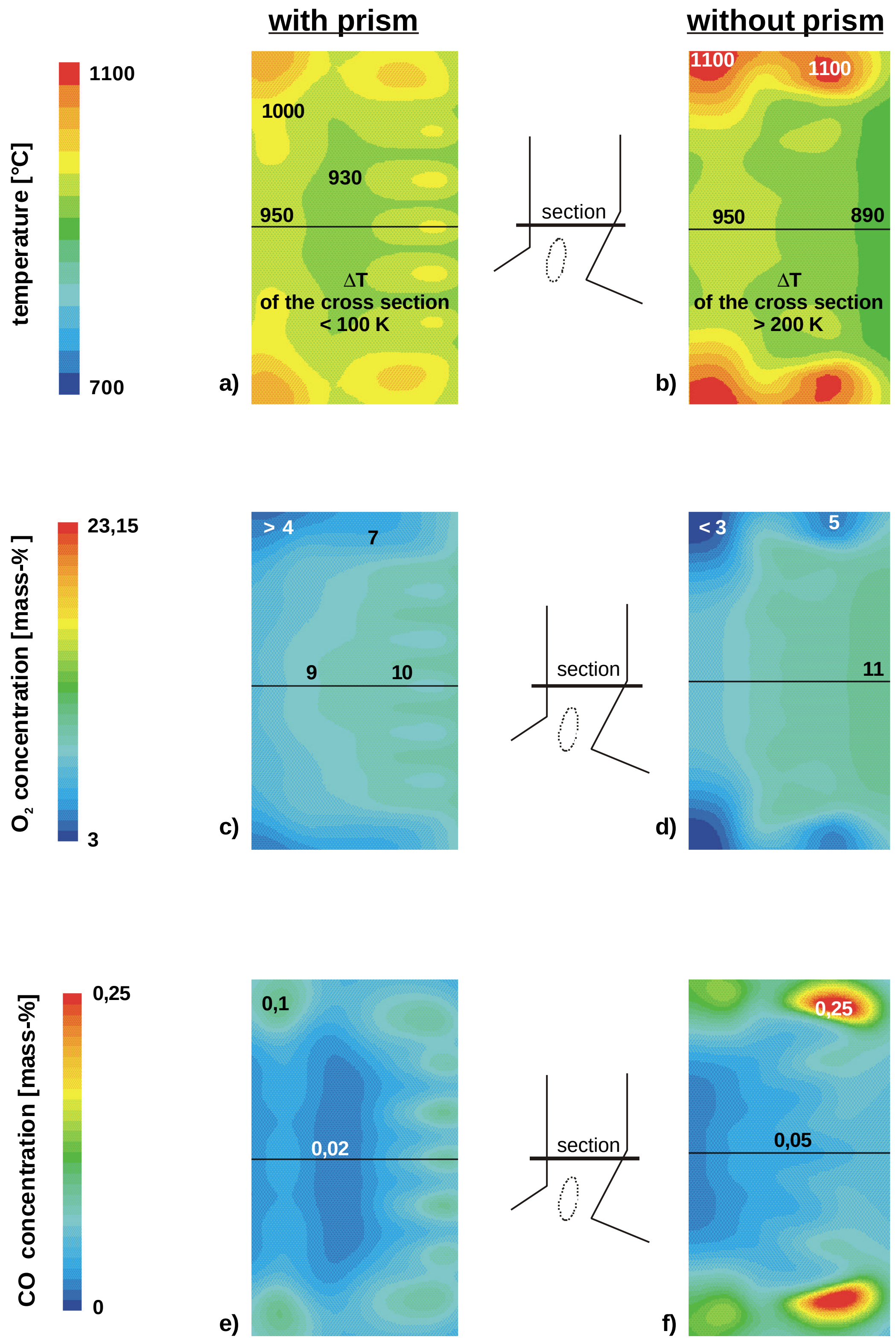
Figure 6 : Incinerator geometry

RESULTS

At first the influence of the new „Prism“ was investigated. The injection angles and the locations of the old secondary air arrays 1 and 4 were not changed. The simulation results display for the case „with prism“ (figure 7e) in contrast to the old design (figure 7f) a very uniform flow field in the radiational part of the incinerator. Especially the recirculation zone (recording window in figure 7f) can´t be observed anymore in figure 7e. The surfaces with a constant velocity of 10 m/s are shown in figures 7a - 7d. Due to the replacement body („Prism“) the cross section at the beginning of the radiational part was reduced considerably. The depth of penetration is of course lower for the case „with prism“, but the whole cross section on the left side of the „Prism“ is full covered. This leads to a good mixing between the pyrolysis gases and the secondary air as is displayed in the figures 8a, 8c and 8e. The distributions of temperature, oxygen and CO are much more uniform as the achieved distributions for the old configuration (figures 8b, 8d and 8f). The temperature difference in the chosen cross section could be reduced from over 200 K to less than 100 K. The difference of the highest and lowest oxygen concentration could be decreased as well. For the mass fraction of CO is even a reduction by 150% recognisable (from 0.25 kg/kg to 0.1 kg/kg).

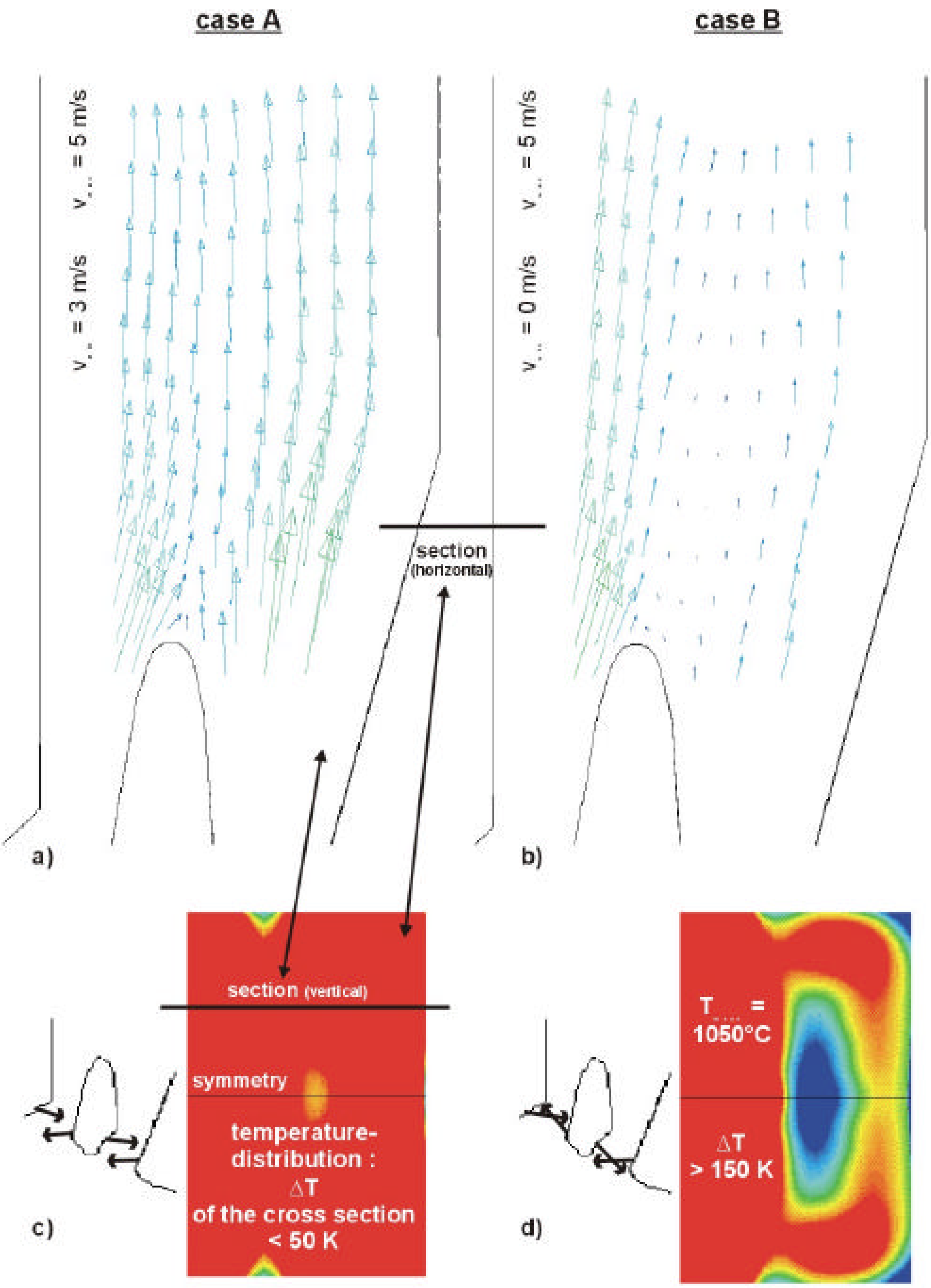


Figures 7 : Influence of the „Prism“ on the flow field
a - d : Surface of constant velocity (= 10 m/s), depth of penetration
e - f : Vector plot (velocity values are for the plotted area)



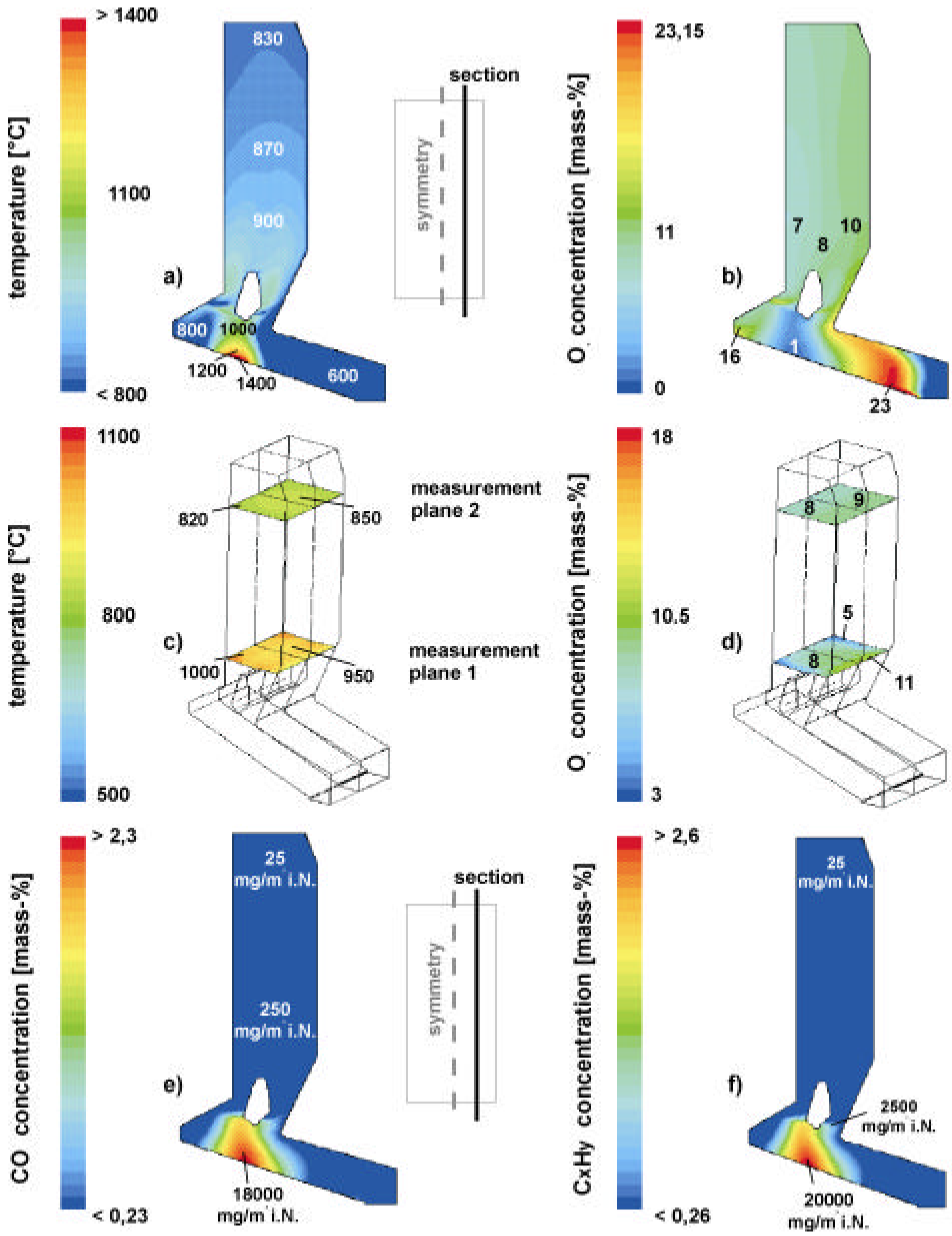
Figures 8 : Influence of the „Prism" on the temperature and species profiles
a - b : Temperature distribution in a cross section
c - d : O_2 concentrations in a cross section
e - f : CO concentrations in a cross section

The next step was to optimise the injection angles of the additional nozzles (nozzle arrays 2 + 3). The direction in case B was chosen in this way, that a crossover grows out of the opposite secondary air beams. In case A nearly the contrary configuration was investigated. Figures 9 a-d show the high influence of the injection angle. The configuration of case A leads to very uniform velocity and temperature distributions (figures 9a and 9c). In case B the flow on the right side of the „Prism“ looks very bad (figure 9b). A dead zone over the „Prism“ is recognisable with the consequence of a considerable higher temperature gradient (figure 9d). For both cases the mean temperature in the chosen cross section was about 1050°C, but the difference between T_{max} and T_{min} could be reduced from over 150 K in case B to less than 50 K in case A.

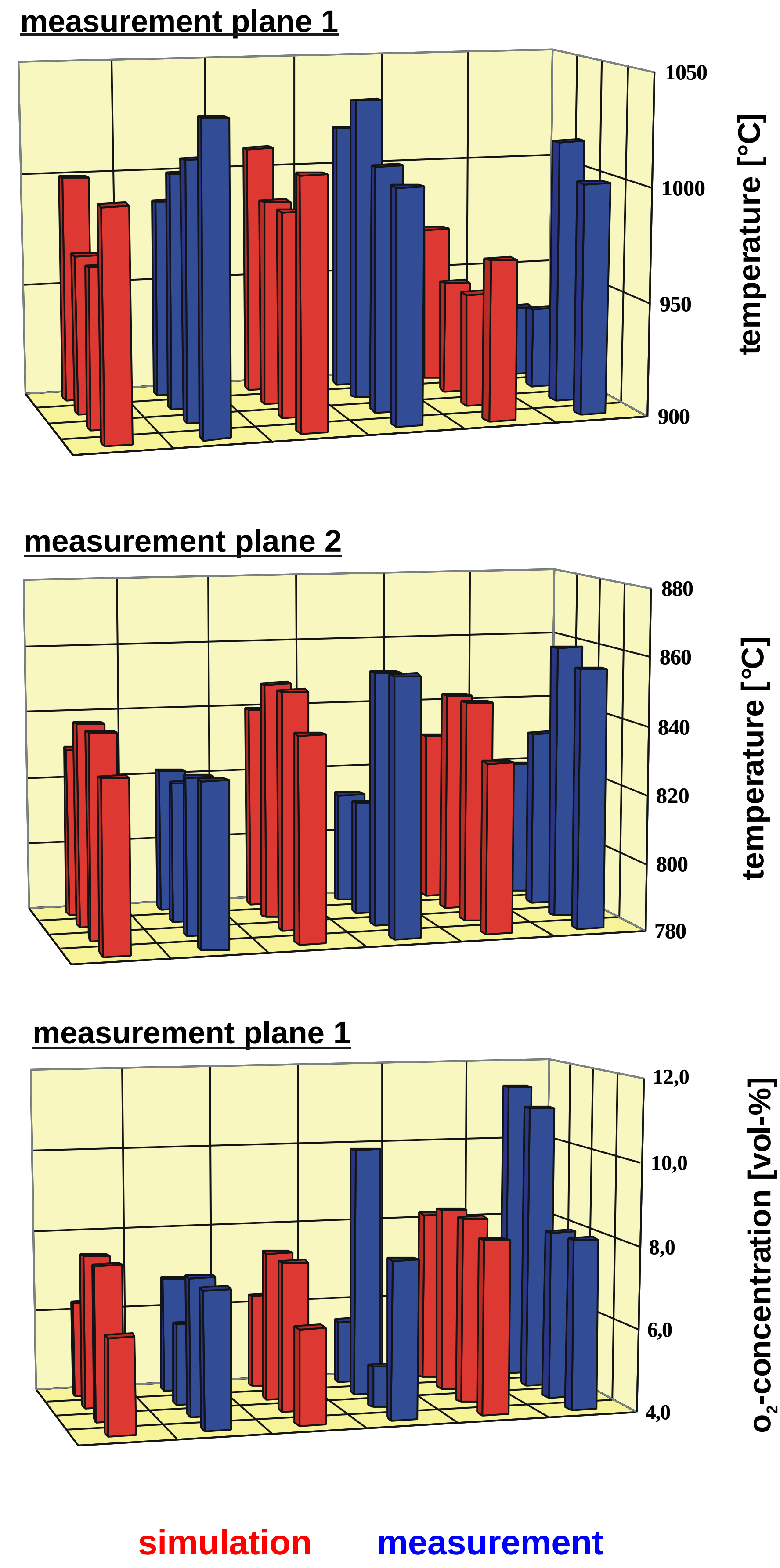


Figures 9 : Optimisation of the secondary air injection angles
a - b : Vector plot / c - d : Temperature distribution in a cross section

For a reference case („optimised“ injection angles and conditions as in figure 6) the simulation results are displayed in figures 10 a-f. The temperature distribution is very homogeneous as well in the vertical section (figure 10a) as in the two horizontal measurement planes (figure 10c). The species profiles in the other four figures look equal, too. The O_2 concentrations are nearly constant in the whole first path (figures 10b and 10d). This indicates that the oxidation of the incomplete products of combustion like CO and C_xH_y (figures 10 e-f) ends practically direct over the „Prism“.
Grid measurements were performed in two horizontal sections for the conditions listed in figure 6 (reference case). Temperatures and oxygen concentrations were measured at 12 points. The comparison between the measured and numerically calculated data is displayed in the figures 11.



Figures 10 : Simulation results of the reference case
a and c : Temperature distribution in a vertical and in two cross sections
b and d : O_2 concentrations in a vertical and in two cross sections
e : CO concentrations in a vertical section, f : C_xH_y concentrations in a vertical section



Figures 11 : Comparison between predicted and measured data

The calculated temperatures in the first plane show values from 950 to 1010°C, the measured temperatures between 931 and 1035°C (figure 11a). Also the tendency that the temperatures decrease to the right side is described correctly. Figure 11b presents the measured and predicted temperatures in the second measurement plane. The calculated mean temperature in this cross section has an amount of 839°C. Compared to the measured mean value (833°C) there is just a difference of 6 K. The oxygen concentrations were only measured in the measurement plane 1. The results can be seen in figure 11c. Except of three very high oxygen concentrations with values over 10 vol-% the difference between the predicted and measured concentrations are very low.

CONCLUSION

This study has demonstrated the very positive result of the „Prism". With the replacement body the width of the path at the end of the main combustion chamber was reduced considerably. In contrast to the old design a full covered cross section by the secondary air beams could be achieved. This led to uniform temperature, velocity and species distributions by the improvement of the mixing processes. The concentration of the incomplete product of combustion CO could be decreased by 150% for example.
The investigations have shown the high influence of the angles of the secondary air injections. The injection angles of the nozzle arrays 1 (-30°) and 4 (0°) of the old design were not changed. „Optimised" injection angles for the two additional nozzle arrays (2 + 3) have the following values :

- nozzle array 2 : -10°
- nozzle array 3 : -5°

Grid measurements in two cross sections of the first path were performed for special conditions. To compare the measured and predicted temperatures and oxygen concentrations this reference case was also numerically calculated. The difference between the experimental and simulated data is very satisfactory.

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