Third International Conference on CFD in the Minerals and Process Industries
CSIRO, Melbourne, Australia
10-12 December 2003

MODELLING OF THE FUEL STREAM AND COMBUSTION IN A ROTARY-KILN HAZARDOUS WASTE INCINERATOR

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ABSTRACT

Hazardous wastes from various industrial processes are normally incinerated with rotary kilns in order to comply with current environmental regulations. They have often very complicated chemical compositions in a variety of physical forms and difficult to characterise. The complex transport phenomena within the incinerator are not well understood, and the incineration process expects large uncertainties in process chemistry and thermal/ emission control. For better understanding of the incineration process, process simulation was conducted using Computational Fluid-dynamics (CFD) code Phoenics to characterise temperature and species distribution in the incinerator. To include all the waste streams in a single CFD model is difficult, and how to define the different waste streams with different calorific values and chemical compositions is a challenge to the CFD modelling. In the current paper, hazardous waste in various forms is firstly converted to a hydrocarbon-based virtual fuel mixture. The combustion of the simplified waste was then simulated with a 7-gas combustion model. The distribution of temperature and chemical species is broadly investigated. Distribution of CO concentration, as a good indicator of emission level for the incineration process, could be used to evaluate the emission control. The predicted temperature distribution has been validated with available measurement data from the operating rotary kiln waste incinerator AVR-Chemie in the Netherlands. New statistical post-processing of the standard CFD-output has been developed to give an overview of the average temperature profile and overall reactor behaviour for process control.

INTRODUCTION

Rotary kiln incinerators are widely used in the incineration of various hazardous wastes such as liquid, sludge, and solids in bulk or in packages. The benefits lie in the drastic volume reduction and the substantial energy recovery. The main objectives of the incineration are the complete combustion of all the waste materials, and efficient recovery of the thermal energy from the off-gases after the waste combustion. Emission control of certain remaining species in the off-gases such as CO and dioxins is an important criterion for the operation. The complete destruction of hazardous compounds depends very much on gas mixing extent of air and various waste streams, the distribution of gas temperature and residence time within the kiln and the secondary combustion chamber (SCC). Due to large variations of waste types and difficulties in feed characterization of physical, chemical and thermal properties, the complex transport and chemical processes within the kiln system are not well understood, and thus the incineration process often anticipates substantial but unpredictable fluctuations of gas temperatures within the system. The temperature fluctuations lead to uncertainties in the process chemistry and difficulties in emission control.

AVR-Chemie, a business unit of the AVR Business Group Industry located in the Rotterdam harbor area of the Netherlands, is specialized in hazardous waste incineration. It operates two rotary kilns at their plant, each with a waste processing capacity of 50,000 tons a year. The newly enforced directive from the European Union (L332) [EU directive, 2000] with increasingly strict emission control requires a better understanding of the incineration process and improved process control for low emissions and less environmental impact. The current European threshold value for carbon monoxide is not easy to comply with. Instead of hourly averaged values, monitoring of half-hour and ten-minute averaging is often required. The formation of carbon monoxide is caused by poor mixing of air and waste streams and insufficient residence time and temperature. A minimum incineration temperature of 1100°C during 2 seconds applies to chlorine bearing waste (> 1% Cl) and a minimum temperature of 850°C for non-chlorine bearing waste [EU directive, 2000]. On one hand, the operators have to comply with strict European guidelines and legislation. On the other hand, the waste supply for incineration is declining and the composition of the waste is frequently fluctuating. The high calorific wastes can be used in energy intensive industries to replace primary fuels, and thus only the most difficult types of waste are delivered for incineration in rotary kilns.

In order to get better understanding of the overall incineration process, research has been carried out in authors' group in close cooperation with AVR-Chemie. Computational Fluid-dynamics has been used to predict more insights of the gas flow, heat transfer and waste combustion within the incineration rotary kiln. CFD is a very convenient and flexible tool to simulate the flow related transport phenomena for large scale industrial processes. For rotary kiln waste incineration a number of modeling attempts concerning flow and heat transfer in the incinerators have been reported [Jenkins et al. 1980; Clark et al. 1984; Wolbach and Garman 1984; Williams et al. 1988; Chen and Lee 1995; Leger et al. 1993; Khan et al. 1993; Jakway et al. 1996; Veranth et al. 1996., 1997; Wardenier and Van den Bluck 1997; Ficarella and

Laforgia 2000], and CFD simulation has been used in a couple cases for hazardous waste incineration [Leger et al. 1993; Khan et al. 1993; Jakway et al. 1996; Veranth et al. 1996., 1997; Wardenier and Van den Bluck 1997; Ficarella and Laforgia 2000]. However, in all the previous modeling work combustion of different types of wastes in one process has not been investigated, and a lot of questions need to be further answered.

The early work from the current project focused more on the thermal contribution to the temperature distribution [Yang et al. 2001, 2002], by using a global combustion model of Spalding (3-gas model). All the waste was averaged and modeled as a global fuel. In general, it proved to be a useful approach, however, it is not able to model the chemical species distribution within the incinerator. In order to model the distribution of major chemical species in the waste combustion system, an extended global combustion model (7-gas model) was applied. Since the diversity of the waste types and large difference in heating value and chemical compositions, the simulation program could not handle directly the multi-fuel system. Therefore conversion of various waste streams to a general fuel which can be used in the CFD model becomes an important step. This has been carried out through the definition of artificial fuel mixture and waste stream optimization. Then the subsequent combustion modelling has been conducted by defining each individual waste stream by using the artificial fuel mixture.

In this paper, the latest model developments and simulation results with the 7-gas combustion model are presented. The prediction of species distribution, especially the CO concentration, gives good indication for the emission level after the incineration process. New post-processing approach was illustrated to present large data output from CFD simulation in a condensed and engineering format. Temperature measurements at a number of accessible locations of the operating incinerator at AVR-Chemie in Netherlands was used to validate the combustion model, and the further needs to validate the model from both thermal and chemical aspects of the waste combustion process are emphasized.

THE ROTARY KILN WASTE INCINERATOR

The incineration system is a standard type of industrial scale rotary kiln waste-incinerator operated at AVR-Chemie. It consists of a rotary kiln and a secondary combustion chamber (SCC). The rotary kiln is 4.2 m in diameter and 11.7 m in length, mounted at a 1-2° angle and it rotates at a speed of 0.07 rpm. The SCC is 6.3 m in width, 5.5 m in depth, and 18 m in height. The thermal capacity of the incinerator ranges from 30 to 40 MW, and the waste processing rate is about 7 tons per hour. A wide range of hazardous wastes with heating value of about 5 to 30 MJ/kg is incinerated in the system.

The waste enters the kiln and SCC in a variety of ways, as is shown in Figure 1: main burner, burner for shredded solid waste, sludge burner, SCC burner, and a couple of lances for various liquid or sludge wastes. A load-chute is used to supply combustion air and previously for supplying containerised solid waste, 14 air lances are installed in SCC to supply additional combustion air. Air is known to leak into the kiln through the front and end seals of the kiln, viewports, and the ash sump. The off-gas leaves the SCC to the waste-heat boiler (WHB) for energy recovery and preliminary dust separation. Molten slag formed in the kiln flows down to the lower end of the rotary kiln and falls into the ash sump located at the bottom of the secondary combustion chamber, which also causes water vapour entering the SCC.

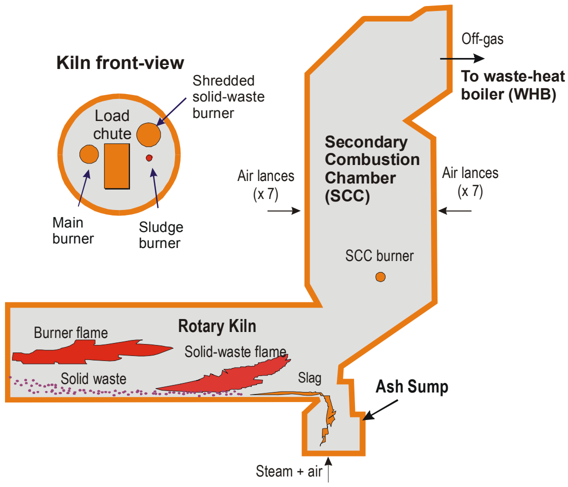

Figure 1: General sketch of the rotary kiln and the secondary combustion chamber.

Previously the solid waste was treated in containers and fed directly into the rotary kiln. Recently, the shredding machine is applied to cut the containerized solid wastes into a mixture of liquid and solid particles. The mixture is then fed into the kiln through a large burner in stead of the whole container, so as to obtain a more homogeneous combustion.

CFD SIMULATION FRAMEWORK

The details of the coupled transport phenomena in the hazardous waste incinerator are very difficult to obtain thorough on-line measurement and high temperature experiments. CFD simulation offers a lot of benefits for investigating coupled transport phenomena of fluid flow, heat transfer and chemical reactions in the incineration system. However, care needs to be taken of the validity of physical models and validation of the results, particularly due to the empiricism introduced by the models of turbulence, multi-phase flow models, combustion etc.

In the current study, the simulation of gas flow and temperature distribution as well as waste combustion in the incinerator has been conducted with CFD code Phoenics 3.4 and 3.5 [Cham 2002]. The governing partial differential equations for conservation of mass, momentum, and energy in a turbulent flow system are expressed by time-averaged 2nd order partial differential equations, and solved with a common numerical algorithm in the code. Due to the turbulent nature of the flow, different turbulence models such as the standard k-ε and its modifications were tested, and the standard k-ε model was finally chosen in the study.

Computational grid

As can be seen in Figure 1, the incinerator consists of a rotary kiln with a cylindrical shape and a secondary combustion chamber (SCC) with a rectangular shape. In order to avoid convergence difficulties, a Cartesian grid was created to construct the incinerator model, with a total 230,394 of cells. In order to obtain the approximate cylindrical shape of the rotary kiln, solid blocks were used to block the inactive regions of the geometry. The grid is shown in Figure 2, where the cell distribution of a side view of the rotary kiln and the SCC, as well as the front view of the kiln is illustrated.

The location and definition of various burners and air inlets are also indicated. Since each waste stream has different thermal value and chemical composition, a fuel-rich and a fuel lean streams were used in different portions to obtain the individual burner input, a central fuel-rich stream surrounded by four fuel-lean streams. A proper definition of a fuel-rich and a fuel-lean streams is required by the 7-gas combustion model of Phoenics which handles only one fuel in a combustion model. In addition, a similar but finer grid of 359,100 cells was used to study effect of extra cooling air from the ventilation system to the rotary kiln cooling ring.

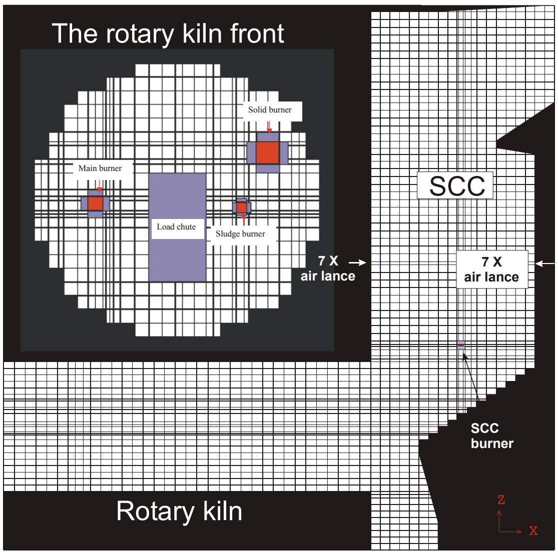

Figure 2: Computation grid of the waste incinerator model, cell distribution: *57×64×86 = 230,394*.

Waste combustion modelling

In order to include the thermal behaviour and major species distribution, waste incineration process has been modelled with 2 available combustion models from the CFD code, the 3-gas and the 7-gas combustion models, as described below. The waste materials were assumed to combust in the gas phase, and the gasification and vaporization process of the wastes was assumed to be complete upon entering the incinerator. This may cause the earlier combustion than in the real system, but this can be regulated by the rate constant in the combustion model to adjust the starting point and the length of the flame. The solid particle or droplet flows were not physically modeled. The heat loss through the furnace walls and energy absorbed into the molten slag was estimated from the overall energy balance and thermodynamics, and the heat loss was subtracted from the energy input of individual waste streams. The errors brought into the results of the simulation models will be discussed in the model validation.

Due to relatively small heat loss of the system (5-10%), the incinerator system is assumed to be adiabatic. Because of the application of adiabatic wall boundary conditions, no radiation model is used in the final model. Earlier tests with Immersol radiation model of Phoenics (Immersed solid radiation model) [Cham 2002] with non-adiabatic walls indicated large uncertainties in the wall heat loss and the resulted gas temperature distribution, due to the lack of detailed inner wall temperature and its distribution, as well as the wall emissivity. The radiation model for the adiabatic walls leads to the same temperature distribution as from the case without radiation model. Although both combustion models could not accurately represent realistic incineration process, they do offer a practical approximation and give a good indication of the temperature and species distribution.

3-gas combustion model

For combustion modeling, a global combustion model of *Simple Chemically-Reacting System* (SCRS, or 3-gas model) of Spalding [Spalding 1979] is used for chemical waste combustion reactions in the earlier phase of the project. In the model, wastes of different types are modeled as vaporized fuels (gases) upon entry. SCRS model focuses on the overall effects of combustion, and it cannot give any detail of the combustion mechanism and chemical species. It involves a reaction between two reactants (fuel and oxidant) in which they combine, in fixed proportions by mass, to produce a unique product:

$$1\,kg\ \text{fuel} + s\,kg\ \text{oxidant} = (1+s)\,kg\ \text{product} + \text{heat} \qquad (1)$$

where s is the stoichiometric oxidant requirement (kg oxidant/kg fuel). This reaction is taken as irreversible. Reaction rates in turbulent flow situations are often more greatly affected by local turbulence than by chemical factors. For these situations the Eddy Break-up (EBU) model is provided, which rests on the hypothesis that only turbulence and fuel concentration affect the reaction rate having the following source term in the mass conservation equation:

$$S_{mfu} = -CEBU \times \min\left\{m_{fu}, m_{ox}/s\right\} \times \frac{\varepsilon}{k} \qquad (2)$$

Where CEBU is the Eddy Break-up reaction constant, m_{fu} is the mass fraction of unburned fuel, m_{ox} is the oxidant fraction. k and ε are the turbulence kinetic energy and its dissipation rate. In the current study it is assumed that the reaction rate for the combustion of the different waste types is turbulent mixing rate limited and the EBU is chosen to determine the reaction rate. On the basis of extensive parametric testing a value at 25–50 for CEBU was found to be reasonable. The stoichiometric ratio s, was taken with value of 6.52, based on the information in the literature Wardenier et al. 1997] and estimation from the average heating value of the waste at AVR-Chemie.

7-gas combustion model

More recently, an improved combustion model was studied in order to understand and predict some chemical aspects of the waste combustion process. Not only the overall thermal behavior could be estimated, but the species distribution could be predicted as well, such as fuel (hydrocarbons), oxidant (O_2), intermediate and final combustion products (CO, H_2, CO_2, H_2O), and the inert component of nitrogen (N_2). An extended SCRS model from Phoenics is explored for this purpose. In order to model the species distribution together with combustion, the first step is to convert the different waste streams into a sort of virtual fuel or fuel mixture. Then the virtual fuel is used for combustion reaction modeling with both equivalent thermal and chemical contribution as the complex wastes. A similar concept has been proposed and used for municipal solid waste (MSW) incineration by Themelis [Themelis 2001]. However, this is still an initial attempt, which aims to utilize the potential of CFD in combination with combustion chemistry. Further justification of such an approach will be addressed when measurement data for chemical species are available.

WASTE COMBUSTION MODELS

Virtual fuel determination

Based on the off-gas composition and mass and energy balance of each waste streams at AVR-Chemie, a virtual fuel is determined. The organic compound was estimated as $C_{102}H_{131}O_{110}$, however, a hydrocarbon has to be found due to the limitation of the CFD code that it cannot handle oxygen at present in the organic compounds. To get the generalised fuel, two constraints are used: (1) heat of combustion = 42,000 kJ/kg, and (2) H/C molar ratio is in a range of 1.3 to 1.7. For all closely related real existing hydrocarbons calculations are carried out to determine the generalised virtual fuel composition. Figure 3 illustrate the concept, where one can see how a poorly defined waste is converted to the better defined fuel. To get the balance of oxygen in the waste, oxygen is introduced to the combustion streams through other oxygen containing compounds such as CO, O_2, or H_2O. Combinations with C_2H_3 or C_3H_4 with other components and for all incoming streams are put in the solver of Microsoft Excel®, both C_2H_3 and C_3H_4, as the main virtual fuel component, are found to fit to the constraints. In this paper further calculations are performed with C_3H_4. C_2H_3 and C_3H_4 have very similar heat of combustion to methane (CH_4), and take gaseous form at room temperature. Here it may be necessary to emphasize that the hydrocarbon C_2H_3 or C_3H_4 is only the main component of the fuel streams, and the used fuel streams in the model are defined as a mixture of the main component. Other allowable fuel component (by the CFD code) of CO and non-combustibles such as CO_2, H_2O, O_2 and N_2, will be explained in the following section (waste stream optimization).

However, it should be noted that the use of a real hydrocarbon to represent the main combustible component is to get the species distribution of the combustion products such as CO, CO_2 and H_2O. The real composition of the wastes is much more complex and the incineration reactions are much more complicated than the assumed "virtual fuel". A major benefit here is that there is a possibility to model the combustion process, and with adjustable model parameters, the thermal effect and distribution of major species in the incineration system could be obtained and evaluated.

Assumed combustion reactions

With the defined chemical compositions of all the waste streams, a two-step combustion reaction scheme is assumed with a primary reaction and two secondary reactions shown as follows:

Step 1 – primary reaction:

$$C_3H_4 + 1.5O_2 = 3CO + 2H_2 \quad (3)$$

Step 2 – secondary reactions:

$$2CO + O_2 = 2CO_2 \quad (4)$$

$$2H_2 + O_2 = 2H_2O \quad (5)$$

The reactions are assumed to be kinetically controlled, and the Eddy Break-up (EBU) is used here to calculate the reaction rate as in the 3-gas model for the turbulent combustion system.

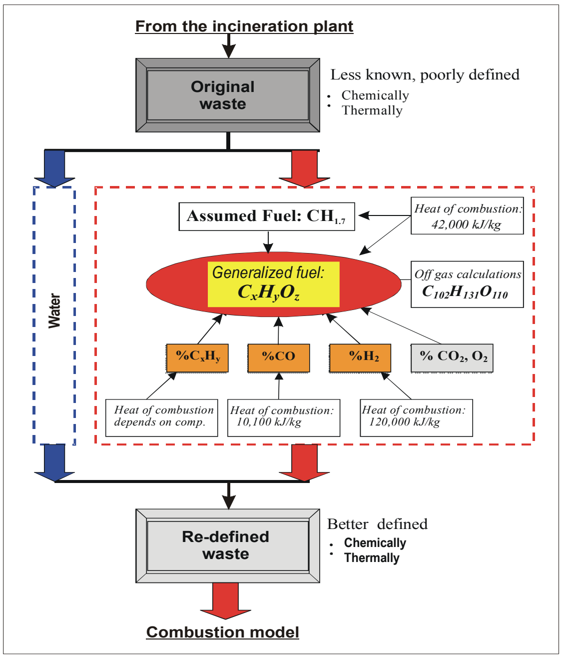

Figure 3: Concept of artificial fuel definition for the hazardous waste incineration plant.

Waste stream optimization

The current CFD code Phoenics has limited the combustion model with only two streams: *"fuel-rich stream"* and *"fuel lean stream"*. Therefore, air and water present in the waste streams have to be distributed into both "*streams*". With these two distinct "*streams*", all the incoming waste and combustion air could be defined by either a pure "*stream*" or a combination of both. For this reason a stream optimization has been made, and Table 1 illustrates the optimised two streams, with which all inlet composition can be determined by mixing different portions of each stream. This composition is based on the assumption that 40% of the sludge burner waste is fed as "*fuel rich*" stream, and 60% as "*fuel lean*" stream, which indicate an extent of premixing.

Thus, the calculated percentages per inlet are shown in Table 2. All pure air supplies through load chute and lances consist out of 100% "*fuel-lean stream*", and waste feeding inlets are mixtures of the "*fuel-rich*" and "*fuel-lean streams*" though separate but adjacent multi-inlets combination. For instance, the main burner is composed of a central "*fuel-rich stream*" and a few surrounded "*fuel-lean stream*" with predefined fractions. Table 2 shows the mass and energy input for all the incoming waste streams as well as additional air supply. For heat of combustion and energy input from each incoming stream, the difference of the

Streams	Compositions (wt. %)						
	C_3H_4	O_2	CO	CO_2	H_2O	N_2	Total
Fuel rich	21.64	15.64	3.09	0.75	4.41	54.47	100.0
Fuel lean	0.28	20.97	0.06	0.00	5.64	73.05	100.0
Heat of combustion (MJ/kg)	46.3	---	10.1	---	---	---	---

Table 1: Chemical compositions of the optimised "*fuel rich*" and "*fuel lean*" streams.

Input data	Compositions (wt. %)								
	Streams	Load chute	Main burner	Sludge burner	Solid burner[1)]	SCC burner	Air lances	Ash sump	Total
Stream distribution (wt. %)	Fuel rich	0.00	34.45	40.00	37.77	13.10	0.0	0.0	--
	Fuel lean	100.0	65.55	60.00	62.23	86.90	100.0	100.0	--
Mass flow rate (kg/h)[2)]		27,000	11,250	3,900	8,193	6,620	9,030	4,000	69,993
Heat of combustion (MJ/kg)	Practice	0.00	3.73	4.00	4.36	1.54	0.00	0.00	--
	Model	0.13	3.65	4.21	3.98	1.47	0.13	0.13	--
Total energy input (MW)	Practice	0.00	11.67	4.33	11.67	2.84	0.00	0.00	30.51
	Model	1.00	11.39	4.56	10.67	2.70	0.33	0.15	30.80

Table 2: Stream distribution, the mass and thermal input for all inlet streams

Note: 1) In definition of solid waste burner, 15.04% was assumed as inert materials reported to slag. The total mass flow rate and the stream distribution are based on the mass flow rate to the gases phase only.

2) The mass flow rate reported here includes the wastes, oxidation air and water content. The waste processing rate is estimated at 7,200 kg/h, based on the operational data in practice.

model data from the real operation conditions in practice is illustrated, and the deviation is relatively small.

SIMULATION RESULTS

Main flow characteristics

It is known that the flow and mixing of the combustion air and fuel vapour determines essentially the waste combustion process. The residence time of the gas particles is crucial for completing the combustion. From the CFD combustion models, the flow pattern and gas mixing are predicted, and Figure 4 illustrates the predicted velocity distribution across a few regions of the incinerator, and a clear view of the complexity of the flow pattern and mixing behaviour could be seen. The 3-dimensional nature and complex mixing pattern are clearly demonstrated. Although the flow pattern has not been validated by flow measurements due to extremely hostile environment within the incinerator, the prediction could well indicate the general characteristics of the gas flow and mixing pattern.

The residence time distribution (RTD) of different gas streams and the in-flight time distribution of each incoming streams have been studied [Yang et al. 2002]. Together with temperature distribution maps, this could to certain extent indicate combustion status.

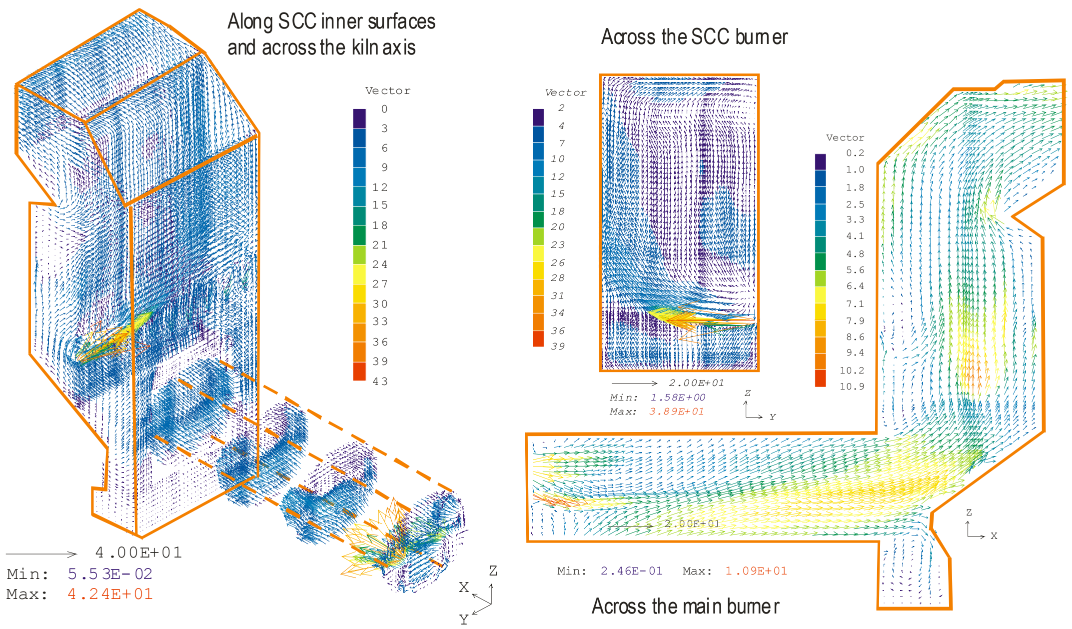

Figure 4: Gas flow pattern inside the rotary kiln and SCC during combustion process.

Temperature Distribution

With the 7-gas model, both the thermal and chemical behaviour of the waste combustion can be simulated. Various scenarios and parameters have been examined, such as the premixing portion of fuel and combustion air, distribution of solid-waste stream between the burner and a solid-bed which may form at the bottom of the kiln. For the later case, a variation between the pure solid-waste burner and pure (100%) solid-bed has been investigated. As an illustrative example, the shredded solid waste assumed to be equally distributed between the solid-waste burner and a solid-bed is used as the show-case in this paper.

Figure 5 illustrates the temperature distribution across the various cross-sections of the incinerator. Figure 6 shows the cross sections from a few essential planes of the incinerator. The combustion flames from all burners or lances as well as the solid bed for part of the solid waste could be clearly seen. However, in the 3-gas model, all the solid waste was fed through the load chute, and the combustion was assumed to take place completely on a solid bed at the bottom of the rotary kiln.

It is important to notice that the distribution of the main combustion air, coming from the load-chute. Due to the

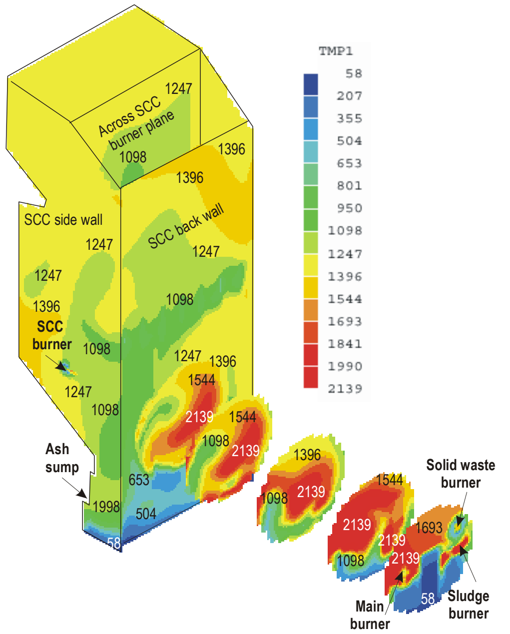

Figure 5: Predicted temperature distribution across the main burner and the SCC burner (7-gas model).

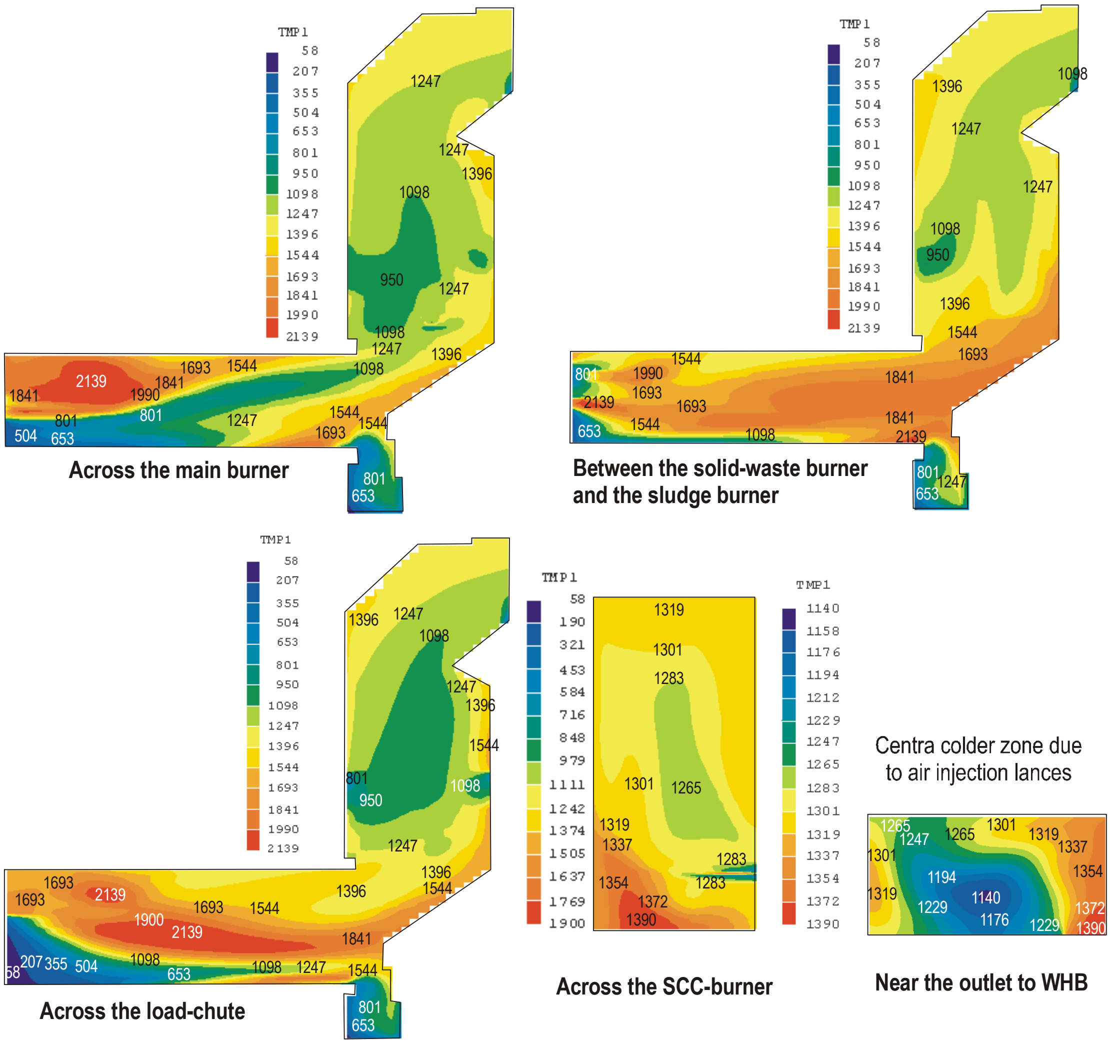

Figure 6: Temperature distribution across various burners, the load-chute and near the outlet (7-gas model).

physical arrangement, the air enters the kiln front from the load-chute at an angle of 50° downward. This causes a poor mixing of the air with waste vapors. From the temperature distribution maps, one can see the colder zone at the lower part of the kiln from both Figure 5 and Figure 6. It can be seen from both figures rather high temperature gradients of the combustion system can be seen. The hotter zones in the kiln lie in the upper-half, and very long flames were formed with a maximum temperature of 2139°C. Combustion from the solid-bed waste takes place somewhat downstream away from the bed, due to the cooling effect of the load-chute air. However, the maximum temperature from the flames is highly dependent on the rate constant (CEBU) of the Eddy Break-up model. In the model shown here, the CEBU constant from both the primary and secondary reactions were set at 2.0. The constant at various levels have been tested, the fine-tuning of the constant needs to be conducted carefully in the next stage. The cooling effect by the cold air from injection lances seems to be significant, and this effect could extend up to the outlet region.

Distribution of Chemical Species

The 7-gas combustion model provides the mass-fraction distribution of all defined 7 chemical species: main fuel component C_3H_4, two intermediate products also as the fuels for the secondary combustion reactions CO and H_2, final combustion products CO_2 and H_2O, and oxidant O_2 and inert species N_2 brought by air. C_3H_4 is present in all fuel-rich streams, but also in minor amounts in the fuel lean streams. CO originates both from the fuel-rich and fuel-lean streams, and from the primary combustion reaction of C_3H_4. From the air lances, minor amount of CO could be observed. It should be noted that H_2O and CO_2 originate from both fuel-rich streams and the secondary combustion reactions.

According to the detailed analysis of the simulation results, all the primary and secondary fuel components are reacted quickly upon entry to the system. Since all the burner streams contain certain amount of oxygen (O_2), partial combustion takes place at early stage upon entry as partially premixed flames. However, the requirement of more air from the surrounding air inlets and majority O_2 supply from load-chute and air lances makes the combustion also partially diffusion-controlled. Therefore, air supply and mixing with the fuel streams become very important.

Figure 7 illustrates the species distribution along the main-burner axis plane and the line profiles along the burner axis. Quick consumption of the fuel components can be clearly seen. The CO and H_2 concentrations depend very much on the relative generation and destruction rate. At present, all the rate constants were set equal, and thus C_3H_4, CO and H_2 follow similar trend. However, if the reaction rate of primary combustion is higher than the secondary combustion reactions, CO and H_2 will exist more appreciably for a long time (more downstream). This will be tested further in the following stage of research. Also obvious is the peak values of both CO_2 and H_2O as final combustion products and CO as an intermediate product lie in the location about 3 m from the burner exit down stream. The minimum value of CO_2 at about 6 m downstream from burner axis is due to the air mixing (bending up from the kiln floor originated from the load-chute).

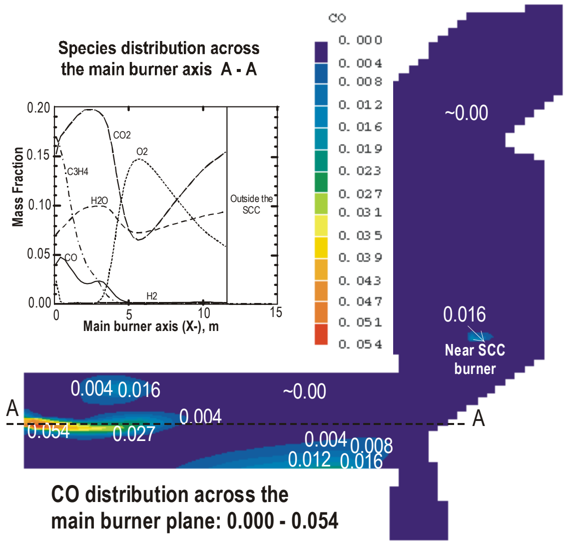

Figure 7: Distribution of CO mass fraction across the main burner plane.

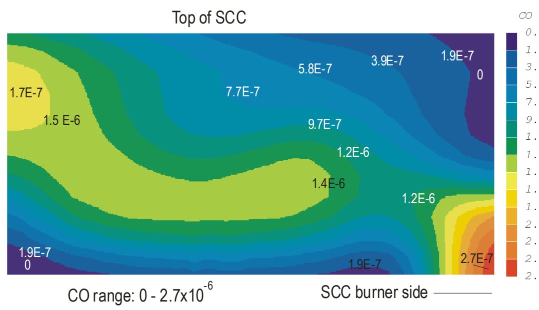

Figure 8: Distribution of CO mass fraction near the outlet of SCC.

From the distribution of CO mass fraction across the main burner plane in Figure 7, only near the burner zones, appreciable CO could be observed. In the majority areas, CO concentration is very close to zero. For a better resolution, a closer look at the lower concentration range is shown in Figure 8 near the outlet of the SCC. Attention should be paid to the CO distribution in the secondary combustion chamber, because of its special status in emissions control. Near the outlet, the CO fraction falls below 3 ppm (wt.). At least in this case, the CO is well combusted in the SCC, according to the simulation results. However, this is a result from a steady state model, which only gives average behaviour of the combustion process.

In addition, other chemical species are calculated from the 7-gas model, and typical distributions of the main fuel and products of the combustion are illustrated in Figure 9. H_2 is not present in the main fuel, and it is only generated as in the secondary fuel component and it is quickly combusted.

Parametric studies

In addition to the case shown above, effects of various parametric changes have been studied. The focus was on the following aspects.

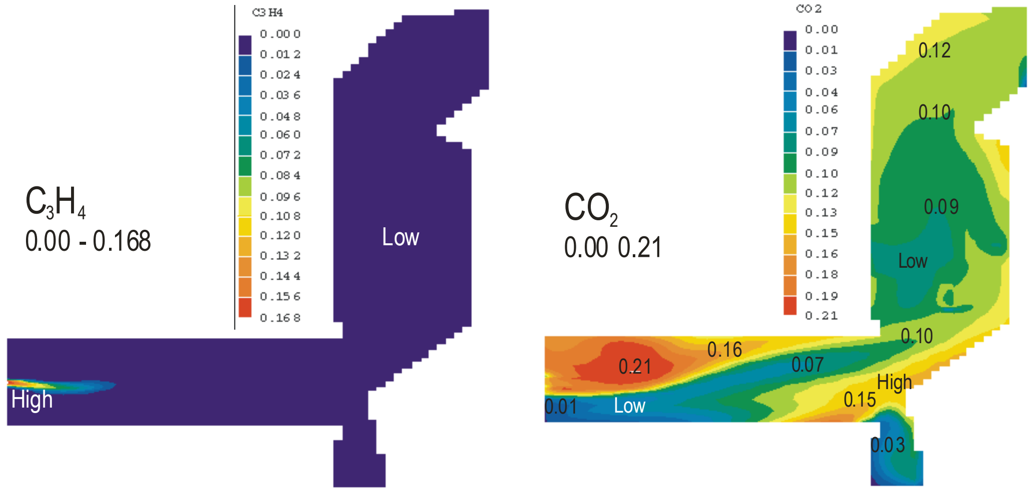

Figure 9: Distribution of C_3H_4 and CO_2 as predicted by the 7-gas combustion model.

Distribution of the solid waste between the solid waste burner and the solid bed: The variation covers the solid waste entry from 100% via the solid waste burner to 100% via the solid bed. This variation causes changes in flame geometry and energy distribution within the kiln, since the solid waste burns more slowly in the solid bed at lower temperatures from the load-chute air. But more realistic distribution needs to be further studied, by using a two-phase flow model in the future.

Rate constant (CEBU) of the Eddy Break-up model of the turbulent combustion system: The tests for the CEBU value of 0.1, 0.5, 1.0, 2.0, and 4.0 have been conducted. It was found that the rate constant in this range does not bring significant changes in the maximum flame temperature, except the case of CEBU=0.1. However, model validation against temperature measurements which will be discussed later shows that CEBU=1.0 gives better fit to the measured temperature profile.

Air preheating: Air preheating was expected to have a big influence on thermal homogenization. Air preheating at different levels were tested from normal 50°C, to 100, 200, 300°C. It shows that the air preheating up to 200°C results in a big improvement in reducing the temperature stratification. This will help to form more uniform combustion reactions, and reduce CO concentration possibly originated from low temperature zones.

Introducing extra cooling air to the kiln: In order to safely utilise the ventilation air from the shredding machine, which contains small amount of combustibles, it is introduced into the rotary kiln through a cooling ring. The influence of this air stream on the combustion and the temperature distribution was studied at different flow rate of 2000 to 6500 Nm^3/hr. The results show that introducing certain amount of extra air through the cooling ring reduces the temperature gradient near the kiln front, and the cooling effect can also protect the refractory lining from overheating.

Air incoming angle from the load chute: Air mixing with fuels was found to be important for the waste combustion. The primary combustion from the load chute is introduced to the rotary kiln at an angle of 50° downward from the horizontal (-50°). The simulation results indicate a large temperature gradient and poor mixing of the air with the waste streams near the kiln front. Thus variation of the air incoming angle was studied from -50°, -10°, 0°, +10° and +50° from the horizontal. The study indicates that horizontal inflow of the air results in the least radial temperature gradients, but also in less mixing with the waste streams. The angle change has to comply with the overall feasibility in practice and a more systematic study should be conducted in accordance with the incoming direction of all the waste streams.

Post processing – statistical analysis

As it is well known, CFD models provide a lot of information in a standard form of various graphical formats and data profiles. However, the large amount of output data are difficult to comprehend for engineering purposes such as in design and in actual process control situation. Therefore, proper post-processing of the results is required to produce useful and handy data sets, which take simple form and are easy to understand and use. By using proper statistical methods, a large amount of CFD output data can be condensed and average information and performance of a reactor could be quickly demonstrated. The condensed information can also be used to construct a database for process control. The following example of temperature averaging illustrates the engineering value of CFD predictions and the possible use of CFD simulation to assist process control.

For non-isothermal and non-uniform gas flow system, simple averaging by cross sectional area could not give correct mean temperature data. Therefore, a mass flow weighted approach is developed to obtain the average temperature and other flow variables (e.g. chemical species). A typical average temperature profile along the main flow direction of the rotary kiln and the secondary combustion chamber can be illustrated in Figure 10. This can be very useful for design and control purposes of industrial furnaces. The data points in Figure 10 also include the maximum and minimum temperatures at each cross-section, and a temperature profile simply averaged with cross-sectional area. The difference between the two different averaging methods could be clearly seen.

Furthermore, a vector approach is developed to point out the average location, an indication of the bias about the geometrical axis of the reactor. The cross section and its symmetrical axis are attached to a co-ordinate system. By means of integration over the whole cross section for the enthalpy and mass flow rate, the centre of enthalpy can be calculated and coupled to a temperature vector. This will make the average temperature a function of the x and y co-ordinates at a given z-location along the reactor axis (suppose z-coordinate is main flow direction). The centre of the average temperature can be calculated based on the temperature moment over the co-ordinates.

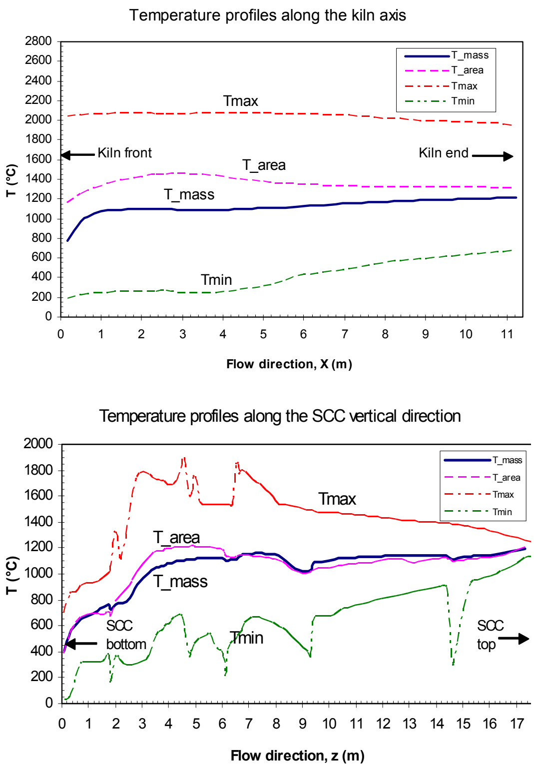

Figure 10: Comparison of temperature profiles along the main flow direction of the incinerator.

MODEL VALIDATION

Model validation plays a critical role in all CFD studies. In the current model system, it is important to obtain measurement data both for gas flow, temperature and chemical species distribution. Because of the hostile environment inside the incinerator and technical restrictions, only the exit plane of the kiln and the secondary combustion chamber furnace interior could be accessed through viewports. In practice, the temperature was continuously measured with radiation pyrometer and 2 thermal couples for process control purpose. In order to validate the combustion models, two temperature measurement campaigns were carried out at AVR-Chemie waste incinerator through the viewports. Both 2-meter and 5-meter long thermocouples were used, and the 5-meter long thermocouple was designed to use flowing water as cooling medium. However, due to time and financial limits, suction pyrometer has not been tested, which would prevent from underestimating the temperature values in the combustion system. Infrared camera was also tried, but no useful results were obtained because of the ambiguity of the focusing point and the influence of the smoke inside the kiln. Along with the measurement campaigns, temperature recordings from permanent thermocouples at SCC were analysed to monitor the process dynamics, and general trend of process stability was observed.

In order to validate the combustion model, validation cases from both 3-gas and 7-gas combustion models were built. The predicted temperature profiles are compared with the measurement data, as is illustrated in Figure 11. During the measurement campaign, the burner for shredded solid waste has not been installed. The total energy input was about 37.06 MW, and the waste

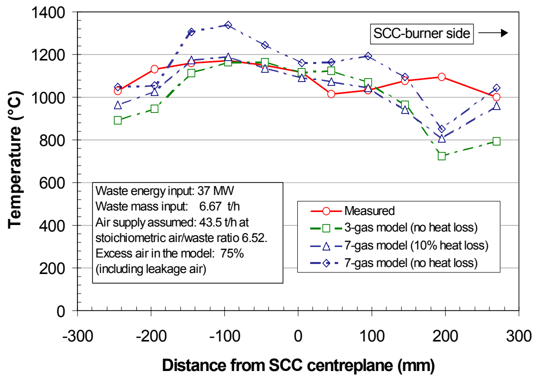

Figure 11: Temperature profile crossing view-ports of the rotary kiln incinerator at AVR-Chemie.

processing rate was 6.67 ton per hour.

Since the temperature measurement lasted about 2 hours, the process was not really running steadily as was monitored from the permanent thermocouples, in spite of the great effort from the operators. If taking into account the process fluctuations, it can be seen that the model predictions are in a reasonable agreement with the measured data. The general trend is well predicted, and the larger discrepancy in all 3-cases near the SCC burner side is caused by the remaining air from the load chute. The 7-gas combustion model predicted somewhat higher temperature in general than the measured data, if heat loss is not subtracted in the model. Negligence of the heat loss from the furnace walls and by the slag formation as well as dust carry-over is estimated approximately at 10%, which could drag the temperature down roughly by 120°C. This means also that the 3-gas combustion model may have predicted lower temperatures than the measured data. The 7-gas model prediction with 10% heat loss shows a better agreement with the measurements. Since no corrections were made for the thermocouple measurements which tend to underestimate the real temperature values, the real temperature profile would be higher than the one shown in Figure 11. This means that the 3-gas combustion model has even worse agreement with the real temperature profile.

Besides the temperature validation, verification of species distribution is another important aspect for the simulation. In the future, measurement of the off-gas compositions will be arranged at AVR-Chemie. Then the 7-gas combustion model could be calibrated more reliably. In the end, both the thermal and chemical behavior of the incineration system could be better predicted and controlled.

CONCLUSIONS

Through CFD simulation of the rotary kiln waste incinerator, more understanding was gained about the waste combustion process. The incinerator is a highly non-homogeneous reactor, with high gradients in combustion species and temperature, especially along the rotary kiln, the primary combustion space. Simulation results indicate that the gas flow is clearly 3-dimensional and complicated because of the multi-gas streams and strong heterogeneous reactive nature of the system, and there is a large room to improve the mixing of the air and the waste streams.

The 3-gas combustion model, especially the 7-gas combustion model could provide a lot of information about the incineration process, provided that the waste streams with very complex nature are properly defined both in chemical and thermal aspects. The present concept of the virtual fuel definition is a novel approach and proved to be a useful exercise and a testing method for the fuel optimization, and any of the similar step is a precondition for more detailed combustion modeling of the complex waste materials. Predicted distributions of certain chemical species in the incineration system give a useful way to monitor the emission level, especially the CO control in the current hazardous waste incinerator. This approach could be extended to other waste incineration systems, if the wastes could be well modelled for a proper combustion simulation. Temperature measurements provided very useful information for calibrating the CFD model, and reasonable agreement has been reached between the measured and predicted temperature data. It is obvious that the detailed combustion modeling of the multi-phase reacting system still requires more in-depth research, and further work with multi-phase flow and combustion of the shredded solid waste is under way.

Post-processing with statistical approach to obtain distribution profiles of average temperature and species as well as the bias from the symmetrical axis adds extra value to the CFD predictions, and more suitable for engineering design and process control.

ACKNOWLEDGMENTS

The authors wish to thank the financial support from AVR-Chemie in the Netherlands and its permission to publish the work. The authors are also grateful to Mr. ir. J. Verwoerd and other the engineering staff of AVR-Chemie for their interests and support to this work.

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