

MODELLING AND CONTROL OF A WASTE TO
ENERGY PLANT
WASTE BED TEMPERATURE CONTROL USING A FEEDBACK
CONTROL LAW

by
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A thesis submitted for the award of the Doctor of Philosophy (Ph.D.) Imperial College
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Abstract

In this dissertation the waste incineration process has been described, an overview of the state of the art control methodologies given and a new approach, based on input/output linearization and extremum seeking has been presented. This approach has been tested on a model appositely designed. The results have shown that it is possible to control the waste bed temperature to certain reference values, with robustness against changes in the waste composition. It is furthermore possible to identify reference values for the waste bed temperature such as the steam flow rate is maximized, while at the same time fulfilling operational constraints.

Contents

List of Figures	3
List of Tables	8
List of Symbols	9
List of Abbreviations	11
Acknowledgements	12
1 Literature Review	13
1.1 Modelling	13
1.1.1 Mixing and solid bed modelling	14
1.1.2 CFD modelling of flame and boiler	14
1.2 Waste Incineration Control	15
1.2.1 Optimization	15
2 Waste Characterization	16
2.1 Solid Waste Composition	16
2.1.1 Household waste	17
2.1.2 Construction and demolition waste	18
2.1.3 Institutional, Commercial and Industrial waste	19
2.1.4 Hazardous waste	19
2.2 Waste Characterization: chemical composition	19
2.2.1 Chemical Composition: Proximate Analysis	20
2.2.2 Chemical Composition: Ultimate Analysis	22
2.3 Waste Chemical and Physical Properties	22
2.3.1 Bulk Density	22
2.3.2 Waste Heating Value	23
3 Process description	26
3.1 How an MSW Incineration plant works.	27
3.1.1 Heat recovery steam generators	29
4 Thermal and chemical processes	31
4.1 Drying	32
4.1.1 Convective Drying	33
4.1.2 Radiative Drying	35

4.1.3	Conductive Heat Transfer	37
4.2	Pyrolysis and gasification	38
4.2.1	Liquid Products	39
4.2.2	Gaseous Products	39
4.2.3	Thermal decomposition kinetics	39
4.2.4	Gasification reactions	40
4.3	Char Combustion	41
4.3.1	Diffusional Combustion	43
4.3.2	Kinetic Burning Rate	44
4.3.3	Overall Burning Rate	44
4.4	Ash Burnout	45
4.5	Secondary Gas Reactions	46
5	Process Modelling	47
5.1	State Equations	50
6	Real Time Parameter Estimation	54
6.1	Background of the invention	54
6.2	Detailed description of the invention	55
6.3	Results and conclusions	56
7	Input/Output Linearization	61
7.1	Zero Dynamics	61
7.2	Non Linear Control	62
7.2.1	Simulation at steady State	64
7.2.2	Variable Waste Composition	67
8	Steam Maximization by using Extremum Seeking	69
8.1	Sensitivity analysis on pile temperature	69
8.2	Extremum Seeking Analysis	72
9	Conclusions	82
	Bibliography	86

List of Figures

2.1	Household waste composition for the German city of Dresden, [1]	17
2.2	Tanner waste triangle [2]	22
3.1	Municipal Solid Waste incineration plant [3]	27
3.2	Scheme of a combustion bed with grates. The blue arrows represent the primary and secondary air. The waste, in brown, is loaded in the funnel via a crane and pushed on the grate with a stocker. The moving grate bars ensure transportation of the waste on the grate, at the end of which the ashes are discharged into the ash bunker.	28
3.3	Schematic representation of a Rankine Cycle with heat and work fluxes.	30
4.1	Spatial progression of combustion on the waste bed.	32
4.2	Superimposition principle for parallel and series configuration	37
4.3	Temperature dependence of coke combustion in the Arrhenius diagram [2]	43
5.1	Model description. The picture shows inputs, outputs and dependencies between the process blocks [4].The thermochemical processes, represented by green squares, are waste dependant, that means that they occur at a different time for different waste compositions. These processes are described by means of mass and energy balances, white squares	48
5.2	Schematic of a single pile. The pile is subdivided into a lower and upper layer, where the upper layer is meant as the superficial layer exchanging heat by radiation with the flame and walls. For modelling purposes only the heat balance for the upper layer is considered. The inputs to the system are primary air and incoming waste rate; the outputs are the outgoing waste rate and the primary combustion gasses.	49

5.3	Schematic of a multiple piles configuration. The waste flows from Pile $n - 1$ to Pile $n + 1$, each pile has its own primary air flow; the secondary air is blown over the waste bed.	50
6.1	Steam flow $[t/h]$ (blue) against steam flow setpoint $[t/h]$ (green). The waste incineration process is modeled using the model described in Chapter 5. The waste composition is assumed constant $\alpha=[0.10, 0.50, 0.35, 0.05]$	58
6.2	Waste flow $[kg/s]$. The waste incineration process is modeled using the model described in Chapter 5. The waste composition is assumed constant.	59
6.3	Regression coefficients θ . The waste incineration process is modeled using the model described in Chapter 5. The waste composition is assumed constant. . .	59
7.1	Input/Output Linearization: The reference temperatures are $T_2 = 700 K$ and $T_3 = 1250 K$. The waste composition is assumed as $\alpha = [0.2, 0.3, 0.3, 0.2]$. The initial conditions for the temperature in the second and third pile were $T_{0_2} = 800 K$ and $T_{0_3} = 1350 K$	64
7.2	Input/Output Linearization: The change in waste temperature is achieved by varying the primary and secondary air flow.	65
7.3	Step Response: Step response to a change in temperature reference for the second and third pile. The system reacts quickly to a set point change, either when only one pile setpoint is changed or when both are. The waste composition is assumed as $\alpha = [0.2, 0.3, 0.3, 0.2]$	65
7.4	Step Response Details: Step response to a change in temperature reference for the second and third pile. The system reacts very quickly to a set point change (red). The time constant is about 3 minutes for a step change of $50 K$	66
7.5	Step Response Controls: Step response to a change in temperature reference for the second and third pile. The temperature is controlled by changing the primary air flow rate under the second and third pile.	66

7.6	Waste Bed Temperature for varying waste composition. The reference values are $T_2 = 750 K$, $T_3 = 1240 K$; we can see how the third pile is virtually unaffected by a change in waste composition. The initial waste composition is $\alpha_1 = [0.2, 0.3, 0.3, 0.2]$ for a lower heating value $LHV = 14 kJ/kg$, the new waste composition is $\alpha_2 = [0.15, 0.3, 0.3, 0.25]$ with a lower heating value $LHV = 14.8 kJ/kg$. The control law is successful in converging to steady state even after a change in waste composition.	67
7.7	Control inputs with variable waste. The new reference values for the temperature in the second and third pile are reached by varying the primary air flow rate. .	68
8.1	Sensitivity analysis of steam flow rate against piles temperature. The steam flow rate (in t/h) has been simulated for different values of the temperatures of the second and third pile, T_2 , T_3 . For each simulation the waste composition is $\alpha = [0.20, 0.30, 0.30, 0.20]$. The steam flow rate value is plotted next to the corresponding curve.	70
8.2	Sensitivity analysis of steam flow rate against piles temperature. The steam flow rate (in t/h) has been simulated for different values of the temperatures of the second and third pile T_2 and T_3 . For each simulation the waste composition is equal to $\alpha = [0.25, 0.25, 0.25, 0.25]$. The steam flow rate value is plotted next to the corresponding curve.	71
8.3	Scheme of control solution. The constrained input/output linearization calculates an input vector such that the temperature targets, θ , provided by the extremum seeking routine are reached. The extremum seeking is described in details in Figure 8.2.	73
8.4	Scheme of the extremum seeking solution. The process output is the steam flow rate y , the target steam flow rate is y^* and d a disturbance. The extremum seeking routine minimizes a pseudo-quadratic cost function providing a target value θ for the temperature in the second and third waste bed piles, see Equation 8.1.	73

8.5	Steam Maximization with constant waste composition: Case 1. This figure shows the steam flow rate obtained in the two cases: Red: Fixing $T_2 = 900 K$, $T_3 = 1350 K$; Blue: Leaving T_2 and T_3 free to vary. The final new values are $T_2 = 991 K$ and $T_3 = 1357 K$. The target steam production is bound to lie in the interval $[37.5, 38.5]$, since, according to Figure 8.1, we expect to find a maximal value for the steam flow in this range.	74
8.6	Steam Maximization with constant waste composition: Case 2. This figure shows the steam flow rate obtained in the two cases: Red: Fixing $T_2 = 900 K$ and $T_3 = 1250 K$ free; Blue: leaving T_2 and T_3 free to vary; The target steam production is bound to lie in the interval $[37.5, 38.5]$, represented by the dashed green lines since, according to Figure 8.1, we expect to find a maximal value for the steam flow in this range.	75
8.7	Steam Maximization with constant waste composition: Case 2. The temperature reference values vary from their initial values of $T_2 = 900 K$ and $T_3 = 1250 K$, plotted in red.	75
8.8	Extremum Seeking with constant waste composition: Case 2. The temperature of the waste bed for the second and third pile is kept to a target value by changing the speed grate V_g , the primary air flow rate F_p and the secondary air flow rate F_s	76
8.9	Waste Lower Heating Value. The LHV for $\alpha = [0.20, 0.30, 0.30, 0.20]$ is plotted in red, for $\alpha = [0.25, 0.25, 0.25, 0.25]$ is plotted in green while the LHV for a variable waste composition with a time constant of 30 minutes and a filtered over two hours is plotted in blue.	77
8.10	Extremum seeking with variable waste: Case 1. Cyan: Fixing $T_2 = 900 K$, $T_3 = 1350 K$; Red: Leaving T_2 and T_3 free to vary. Blue: $T_3 = 1350 K$, T_2 left free to vary; The target steam production is bound to lie in the interval $[37.5, 38.5]$. The waste composition varies with a time constant of 30 minutes and a filter time of 2 hours.	78
8.11	Extremum Seeking with variable waste composition: Case 1. The initial reference values for T_2 and T_3 , in red, are plotted against the output values θ of the extremum seeking, in blue.	79

8.12	Extremum Seeking with variable waste composition: Case 1. The temperature of the waste bed for the second and third pile is kept to a target value by changing the speed grate V_g , the primary air flow rate F_p and the secondary air flow rate F_s	80
8.13	Extremum seeking with variable waste: Case 2. Red: Fixing $T_2 = 900\text{ K}$, $T_3 = 1250\text{ K}$; Blue: Leaving T_2 and T_3 free to vary. The target steam production is bound to lie in the interval $[37.5, 38.5]$, plotted with a dashed green line. The waste composition varies with a time constant of 30 minutes and a filter time of 2 hours. The waste has the LHV shown in Figure 8.9.	80
8.14	Extremum seeking with variable waste: Case 2. The initial reference values for T_2 and T_3 , in red, are plotted against the output values θ of the extremum seeking, in blue.	81
8.15	Extremum Seeking with variable waste: Case 2. The temperature of the waste bed for the second and third pile is kept to a target value by changing the speed grate V_g , the primary air flow rate F_p and the secondary air flow rate F_s	81

List of Tables

2.1	Household waste composition for the city of Duesseldorf, from 1980 to 1990 [2]. The waste fraction is expressed in % of weight.	18
2.2	Heating value of different fuels.	24
4.1	Heat conductivity for waste components [2].	38
4.2	Yields of pyrolysis products from different refuse components [5].	40
4.3	Overall kinetic data for char combustion including corrections for boundary layer diffusion and surface exothermicity [6]	45
8.1	ES Parameters for the test with variable waste test. The parameters have the meaning as in Figure 8.2.	79

Table of Symbols

Symbol	Definition	Unit
A	Area	$[m^2]$
A_s	Surface Area	$[m^2]$
d_p	particle diameter	$[m]$
D_o	Oxygen Diffusivity	$[m^2/s]$
E_a, E	Activation Energy	$[kJ/kg, kJ/kmol]$
h	Convective heat transfer coefficient	$[W/m^2K]$
k_0	Frequency factor	$[1/s]$
k_{vol}	Volatisation Rate	$[1/s]$
k_{chem}	Kinetic Burning Rate	$[1/s]$
k_{diff}	Diffusional Burning Rate	$[1/s]$
k_{eff}	Overall Burning Rate	$[1/s]$
M_c	Molar mass of carbon	$[kg/kmol]$
n_p	Number of particles	$[-]$
$p_{o_2, \infty}$	Oxygen partial pressure	$[-]$
R	Universal Gas Constant	$[kJ/kgK]$
Sh	Sherwood Number	$[-]$
T_g	Gas Temperature	$[K]$
T_s	Solid Temperature	$[K]$
T_m	Average Temperature	$[K]$

Greek Symbol	Definition	Unit
α	Waste composition	$[-]$
ϵ	Emissivity coefficient	$[-]$
ϵ_p	Porosity Diameter	$[m]$
ϵ	Error	$[-]$
λ	Conductive Heat Transfer Coefficient	$[W/mK]$
ρ	Density	$[Kg/m^3]$
η	Efficiency	$[-]$
η	Dynamic Viscosity	$[kg/m, s]$
ν	Air Velocity	$[m/s]$
v	Specific Volume	$[m^3/kg]$
κ	Air Conductivity	$[V/m, K]$
Φ	Mechanismusfaktor	$[-]$
σ	Stefan-Boltzmann Constant	$[J/s, m^2, K^4]$
θ	Regression Parameter	$[-]$
θ	Probing Signal	$[-]$

List of Abbreviations

ASTM	-	American Society for Testing and Materials
CFD	-	Computational Fluid Dynamics
DAF	-	Dry Ash Free
ES	-	Extremum Seeking
EU	-	European Union
FLC	-	Fuzzy Logic Control
FLIC	-	Fluid Dynamics Incinerator Combustion
HHV	-	Higher Heating Value
IR	-	Infrared
LHV	-	Lower Heating Value
MSW	-	Municipal Solid Waste
PID	-	Proportional Integral Derivative
SI	-	International System of Units

Acknowledgements

This research has been conducted in cooperation with ABB Switzerland, Power Automation Technologies. Moreover we wish to thank Eduardo Gallestey and Alex Stothert for their work in developing the model in [4] used throughout this study. A special thank to Professor Alessandro Astolfi for his guidance and to Maria for her friendship and support.

Chapter 1

Literature Review

Municipal and industrial wastes have been treated in waste incineration plants since the beginning of the 20th century. This is done mainly to reduce the volume of the waste which has to be deposited. In addition, the incineration process transforms environmentally hazardous components of the waste, such as aromatic hydrocarbons or organic solvents, into harmless compounds. Incineration plants also convert the combustion heat released into steam or electricity or both. The steam can be used for industrial processes or for district heating and the electricity is usually fed into the national grid. In 1999 the European parliament has passed a law that forces every country in the European Community to stop depositing municipal waste without any treatment no later than 2005, making then incineration the only feasible treatment [7]. Waste incineration on packed bed, either fixed or moving, has been a common practice for more than once century. As environmental concerns and waste production increase, the need of a better overall process efficiency has lead to many studies. A better efficiency can be achieved for instance by increasing the mechanical and thermal efficiency of the boiler or the material properties and by improving the process control and optimization. Given the nature of this study we altogether skip literature on cycle optimization and material improvement and concentrate on modelling for controlling purposes and existing control approaches.

1.1 Modelling

The waste incineration process is very complex, mostly due to a high variability of the fuel characteristics. In order to design, operate and maintain moving, packed-bed incineration plants, the burning process has to be understood in detail and the modelling approach has to be rigorous to take into account all the interactions and nonlinearities in the processes. Two main issues in waste incineration modelling are the simulation of the solid bed and the

simulation of the gas phase. These two worlds interact via the primary air that provides the oxygen to combust the solid combustion products.

1.1.1 Mixing and solid bed modelling

A key feature of incinerator combustion is the mixing of solid material on a moving bed, obtained by rollers or a moving grate. As this study verges on an incineration plant with moving grate, the literature here presented refers to such plant typology. The mechanical mixing is designed to provide a conveying and mixing action to move the waste through the furnace and allow complete combustion. Though the importance of proper mixing is clear, existing grates often don't do it adequately. This leads to very high volumes of air, to achieve complete combustion. As a consequence the whole boiler and the gas cleaning section are oversized; the ash carry-through too high and there is a substantial risk of having unburnt carbon in the ashes [8,9].

1.1.2 CFD modelling of flame and boiler

Studies on solid mixing are often carried out on small scale fixed bed, using coloured tracers [9–11]. Such tests are used to validate experimental software models. One such example is the 2-D bed-modelling program FLIC [8,10], in which the whole bed and the freeboard area above are divided into many small volumes. The transport equations concerning the flow, heat transfer and combustion of the solid and gas phases are then discretised over these volumes or cells, and solved iteratively. The computation gives the results on the distributions of temperature, waste components, gas species and other properties within the bed and in the freeboard space. Individual process rates such as moisture evaporation, volatile devolatilization and char burning can easily be monitored and analysed [10]. Such softwares are used to give the boundary conditions for CFD simulations of the over bed area and boiler [2,10]. This kind of modelling is computationally very demanding and is applicable only for off line studies. It is mainly used in the design phase or for performance analysis on existing plants. As such, it is quite out of this work's scope. Nonetheless the results can be used for comparison. Another aspect that has often been investigated is the representation of waste composition and the estimation of its calorific value, [12,13] and [14], since characterizing correctly the fuel quality is extremely important both for design and for modelling purposes.

1.2 Waste Incineration Control

The successful operation of the incineration process is intimately linked with many uncertainty factors, such as waste composition, heating value, moisture content, feed rate, stocker speed, preheated air and boiler efficiency. The combustion system dynamics are very complex and the state variables are so highly coupled that, according to [15], it is relatively difficult to decouple the system adequately to implement control strategies. Moreover, the discontinuous feeding and grate movement brings hardly unavoidable oscillation in the flue gas temperature and as a consequence in the steam flow [16], [17]. Conventional control strategies rely mostly on the use of PID controllers [18]. In the past few years the use of both classical and adaptive fuzzy logic has been widely investigated and used, with encouraging results [15,17–19]. Conventional automatic combustion control was frequently found not sufficient enough to handle these highly nonlinear systems and to maintain a reasonably stable condition during the incineration process [18]. Fuzzy Logic Controls have demonstrated their feasibility in various industrial applications to assist in stabilizing the on-line upset condition. The role of fuzzy systems in control may vary depending on the required assistance in the incineration process. In any circumstances, design of FLCs requires determining the input and output variables, parameters of membership functions, and fuzzy control rules. Identification of a suitable set of quantitative control rules via an analytical approach, such as neural network model or rough sets theory, is often difficult and challenging. Infrared thermography can be used together with fuzzy logic in hybrid solutions to improve the performance of standard controller [20].

1.2.1 Optimization

The objectives to be considered to assure optimal performance may be grouped in three categories: the maximization of economic performance (e.g. throughput), minimization of products of environmental concern such as NO_x, dioxins, and carbon-in-ash and ensuring that operational constraints such as temperature levels and oxygen concentration within the combustion chamber are not violated. The task of optimizing waste incineration plant performance is complicated by the trade-off that must occur when attempting to improve conflicting objectives. Maximizing throughput, for instance, conflicts with minimizing emissions and performing within operational constraints. In [21] it is proposed the use of Multi-Objective Evolutionary Algorithms to optimize waste incineration plants and to provide a decision support tool for operators where trade-off in plant performance objectives may be transparently perceived.

Chapter 2

Waste Characterization

This chapter treats the characterization, composition and physical and thermal properties of waste, with special attention to solid municipal waste as conventionally burnt in incinerators. In Section 2.1 we define the main waste streams, in Section 2.2 we describe how waste composition can be defined while in Section 2.3 the focus is on waste chemical and physical properties of technical interest.

2.1 Solid Waste Composition

Most of the material that is incinerated falls within the class "solid waste". Unfortunately, this highly heterogeneous solid waste is very difficult to deal with as an engineering material, however, for incinerator analysis and design purposes, it can be usefully considered as a relatively discrete material with acceptable reproducible properties and characteristics, clearly if considered on a long averaging time. According to [7], mixed municipal waste means waste from households as well as commercial, industrial and institutional waste - which because of its nature and composition is similar to waste from households - but excluding fractions indicated in the Annex to Decision 94/3/EC (4) under heading 20 01 - that are collected separately at source - and excluding the other wastes indicated under heading 20 02 of that Annex (and following updates [22]); such wastes are defined as hazardous. Solid waste is therefore a very heterogeneous material and in this context, composition refers to the category of material (paper, glass, etc.) in the waste streams. Composition data based on waste streams are low cost to obtain and can rapidly be applied to large quantities of waste. They can be translated in to mean overall chemical composition by taking the weighted average of the chemical composition of specified components. Lastly, data on a categorical basis are directly usable to estimate the potential for materials recovery. In many instances, the waste streams of interest cannot be

directly sampled. Under such circumstances, data from other municipalities can be useful as an indicator of mean refuse composition. An examination of refuse composition data from across the United States [23] shows a great variability, reflecting local practices regarding the wastes accepted at landfills or incinerators, economic level of the citizens incorporation of commercial wastes etc. The main streams, originating from various human activities, are described in the following paragraphs.

2.1.1 Household waste

The expression household waste means the waste produced by domestic human activities. The household waste is characterized by a strong heterogeneity; to better analyze its composition we subdivide it in four further subgroups. This grouping serves also for the determination of the quantitative and qualitative composition. Figure 2.1 shows the composition of municipal solid waste in the German city of Dresden, while Table 1 shows the waste composition from year 1985 to 1993 in the German city of Duesseldorf.

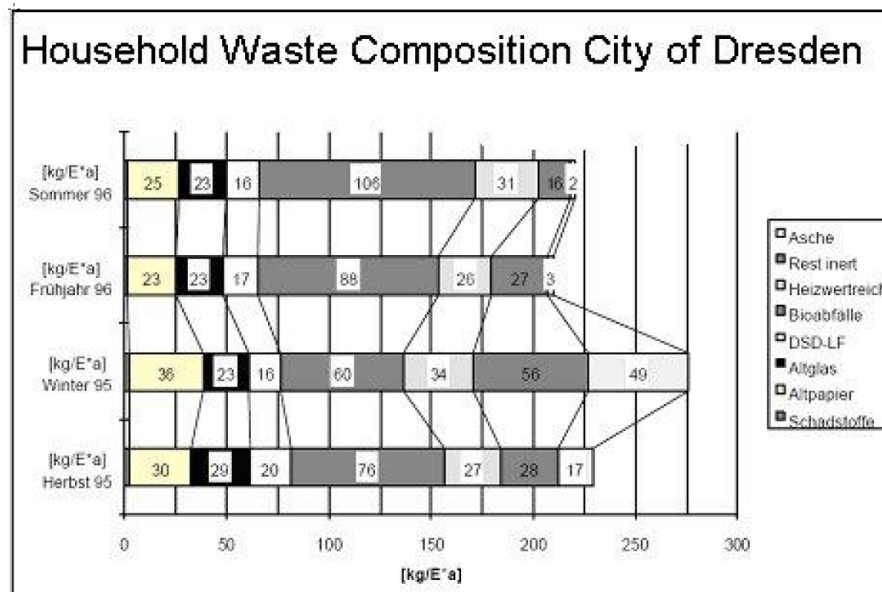


Figure 2.1: Household waste composition for the German city of Dresden, [1]

- Group 1: Materials that burn or can be composted, food and kitchen leftovers, paper and shredded carton, textiles without plastic and yard wastes.
- Group 2: Material that can only be combusted, wood, unshredded carton, textiles with plastic components, rubber and leather, cotton waste.

- Group 3: Material that cannot be burnt or composted, glass and porcelain, stones, metals.
- Group 4: Fine waste (until 8 mm diameter), ashes, sands and organic material of a small dimension.

Waste	Year					HHV[kJ/kg]			
–	1980	1985	1988/89	1985	1990	7/1993	6280	8374	10467
Household Waste						73,9			
Market Waste						1,72			
Paper and Carton	20	17,9	16	27,8	27	4,77	10,74	24,57	33,94
Wood						9,71	5,98	9,41	18,42
Plastic	6,1	5,4	5,4	6,2	5	1,92			
Verbundstoffe	0,9	1,1	3	1					
Textiles	1,5	2	2	3,1	2,6		5,19	7,8	
Rubber, Leather						0,15	0,78	1,38	0,53
Disposable Nappies	2,9	2,8	2,8						
Organic Wastes	25,7	29,9	29,9	38,1	30,0	-	36,9	24,6	12,3
Road Waste						5,42	22,34	16,13	9,93
Fine Waste 0-8 mm	8,60	10,2	10,1	1,9					
Medium Waste ≥ 8-40 mm	3,9	3,2	3,2						
Garden/Park Waste						1,9	0,25	0,48	630
Hazardous Waste	0,4	0,3	0,4			0,34			
Metal	3,9	3,2	3,2	4,4	6	3,58		3	2,42
Glass, Ceramic	11,5	9,1	9,2				11,2	9,7	8,6
Minerals	2,9	2,0	2,0				2,81	2,05	1,29
Other Waste	4								
Additional Humidity						1,66	1,13	0,62	

Table 2.1: Household waste composition for the city of Duesseldorf, from 1980 to 1990 [2]. The waste fraction is expressed in % of weight.

2.1.2 Construction and demolition waste

Waste generated in the course of construction and demolition activities can comprise a large fraction of the total waste disposal requirements in metropolitan area. In the courses of construction activity, waste is generated in proportion to the usage of various building material. The fraction lost, thus contributing to the municipal waste stream, differs widely between these materials. Estimation of the quantities and composition of this waste can be made based on the floor area of the building to be constructed or demolished and the general structural type of the building, and are volumetric. Conversion factors are provided to readily convert between the volumetric and the mass bases. Using the volume-to-mass conversion factors the waste generation intensity from construction activity can be estimated, [23]. Data from Germany [2]

indicate that the average compositional breakdown of typical construction site waste is 64.85% mineral matter, 31.24% combustible matter and 3.91% metal.

2.1.3 Institutional, Commercial and Industrial waste

Solid waste from institutional and commercial sources (schools, office building, stores, small business) almost equal that generated by residences. Industrial waste generation can exceed the combination of residential and commercial wastes. Yet, with their importance apparently obvious, little published data exist [23]. These wastes can be defined as "household-like" wastes. With this name are described those waste materials originated from commercial and industrial activities, that appear in smaller quantities than in household waste and as a consequence can be disposed of in the same plants as the municipal waste. Given the variety of industrial processes, on the contrary of the commercial ones, a waste analysis is required to determine if the industrial waste can be considered household-like or has to be treated separately.

2.1.4 Hazardous waste

Those industrial wastes that don't fit into the description of household-like waste, must be disposed of separately, as hazardous waste. As hazardous waste can be classified all those material that are dangerous for the environment or have a negative health impact for living organism, that means materials that are toxic or carcinogenic, or, more precisely, all that wastes indicated in [22]. In a more general sense, it belongs to this group also wastes that can cause odour hazard or are in such a huge amount that they can not be treated together with household-like waste, although they present household-like characteristics. Incinerators that burn such materials are, perforce, hazardous waste incineration, and they are subjected to a special regulation.

2.2 Waste Characterization: chemical composition

In the previous paragraph we have described waste in terms of its main material streams, as they can be identified in the waste at its collection point. Another way of characterizing the waste is through its chemical composition. A first approach is to define it through its fractions of water, inerts, combustibles (proximate analysis). These values can be derived by the stream analysis described in the previous sections. Lastly, the waste can be described by its main chemical components carbon, hydrogen oxygen, sulphur etc. In this case we talk of ultimate

analysis.

2.2.1 Chemical Composition: Proximate Analysis

The material composition of waste has a relevant influence on its combustion behaviour. Moreover the combustion process together with the waste composition and the volatilisation characteristics defines the flue gasses and ash composition; therefore it is not possible to determine the behaviour during combustion only from the fractional division of the waste. The chemical composition has to be determined for every meaningful fraction. To simplify this description, these fractions are grouped, in analogy to the standard fuel analysis, in combustibles, inerts and humidity, also referred to as water content or moisture.

Proximate Composition: Combustibles

The combustible fraction in the household waste consists of paper, wood, plastic, textiles and food rests. These subcategories are described in the following chapters.

- **Wood and Paper:** Paper, wood and to a certain extent food, consist mainly of carbohydrates. The wood fraction in the waste bulk, lays at around 34,2 % in weight. Paper consists mainly of cellulose; newspaper paper and carton contain on the contrary a relatively high fraction of lignin and other sugars. The heating value of newspaper paper and carton does not therefore differ too much from the wood's one. Proteins, which are sometimes contained in food rest, have, as a consequence of the higher carbon content and a higher fraction of available hydrogen, a significantly higher heating value than carbohydrates. This applies even stronger for fats. Even when recycling takes place, old paper is no more reusable after having been recycled 5-8 times, because the fibers are destroyed and is then burnt.
- **Plastic Materials:** Into the plastic materials category fall plastic, rubber as well as leather and textiles. Around fifty different kinds of plastic materials are contained in household waste, although about 90% in weight is given by standard plastic materials such as polyethylene, polypropylene, polyvinyl chloride (PVC) and polystyrene. Plastic not only shows polyhydrocarbonate chains, but also chlorate hydrocarbonate polymers, which, show very variable heating values. Plastic resins are also used in a variety of container and packaging products and a wide variety of other resin types used in other plastic containers, bags, sacks, wraps and lids. A series of plastics, amongst which polyamide

and polymethane, are constituted for about 19% in weight of nitrogen. Except phenol- and melaminic resins, none of the main plastic materials contains sulphur. The most important fluorurate plastic is polytetrafluorethylene. The used amounts are anyway very low and concentrated to special applications. The chlorine bounds are the main constituent of PVC. The average plastic percentage in household waste lays at around 6-8% in weight, whereas the PVC wastes contributes with 18% to the total plastic fraction. Chlorine bounds are also contained in cooking salt, road salt, paper, wood, vegetables leftovers, food waste and ashes. The predominant source of rubber in municipal solid waste is rubber tires from automobiles and trucks. Other sources of rubber and leather include clothing and footwear and other miscellaneous durable and non-durable products. Textiles in municipal solid waste are found mainly in discarded clothing, although other sources were identified to be furniture, carpets, tires, footwear, and other non-durable goods such as sheets and towels.

Proximate Composition: Inerts

The fraction of inert materials in household waste embraces glass, ceramic, combustion ashes, external ashes, metals and other minerals. The meaning of inerts for the combustion process is that they subtract, in form of ashes and slags, a huge heat amount from the combustion. Due to this heat loss, inerts have a slowing effect on combustion. As further inert materials can be considered N_2 and Cl contained in the waste and first released during combustion.

Proximate Composition: Humidity/Water Fraction

A slowing effect on combustion, similar to the one from ashes, is given by the humidity/water fraction. This is due to the endothermic evaporation of humidity/water content. The required heat must be supplied by the combustion.

Proximate Composition: Fuel Triangle

A clear and understandable representation of the combustible characteristics of different fuels is the so-called fuel triangle, from Tanner. The sides of the triangle give the fraction of water, ash and combustible material in weight fraction, whose sum is equal to 100% [1], [2]. This triangle has been expanded by Urnab to include the heating value scale. Given a composition, the heating value of the corresponding waste can be determined and conclusions on its combustion behaviour can be deduced.

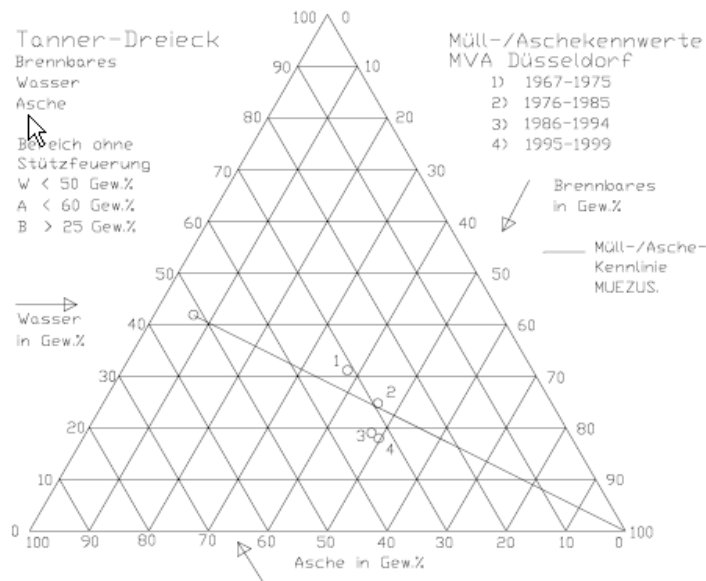


Figure 2.2: Tanner waste triangle [2]

2.2.2 Chemical Composition: Ultimate Analysis

The ultimate analysis (also known as elemental analysis) gives a waste description in terms of its main chemical components C , H , O , N and S .

2.3 Waste Chemical and Physical Properties

For an optimal combustion, other parameters than the composition are relevant. They can be divided in physical and thermal parameters. Hereunder we describe the most important parameters, such as bulk density, lower heating value, and ash fusion temperature. A special relevance is given to the waste lower heating value and the methodologies to estimate it, since it is based on that parameter that the waste can be classified as fuel.

2.3.1 Bulk Density

The term bulk density defines the average density of the waste as it is, including the empty spaces between the single waste particles. The total volume of the fresh waste is composed of:

- The specific solid volume v_F of the actual solid bodies in the sample volume
- The specific hollow volume v_H of the actually empty space, such as the internal volume of containers, jars, boxes, bottles etc.

- The specific void v_L volume given by the empty spaces between the solid bodies

The specific bulk volume is therefore given by

$$v_S = v_F + v_H + v_L \quad (2.1)$$

The reciprocal of the solid volume gives the solid density ρ_H , the reciprocal of the hollow volume gives the hollow density ρ_H and the opposite of the bulk volume gives the bulk density ρ_S . In a heterogeneous mix, such as for example pebbles of different diameter, the void volume reduces itself more and more as smaller the smallest diameter gets for a growing number of particles. The maximal density occurs when the next smaller grain fills exactly the void. With bodies of irregular shape, generally larger voids occur compared to the case with spheres. Loose waste in bags or buckets has an average of about $90\text{-}120 \text{ kg/m}^3$, while pressed waste density lays around $350\text{-}550 \text{ kg/m}^3$. Normally the waste at the moment is deposited in the bunker has a density of about 200 kg/m^3 , while the one, wetter and fermenting, at the bottom, an higher density of about 500 kg/m^3 . The average density of the waste coming on the grates lays around $209\text{-}220 \text{ kg/m}^3$ for waste with a calorific value in the range $4187\text{-}12560 \text{ kJ/kg}$.

2.3.2 Waste Heating Value

The Higher Heating Value (HHV) is the specific heat released by the complete combustion of one unit of weight, including the latent heat of vaporisation of the water formed during the combustion. By subtracting from the higher heating value the latent heat of vaporisation, one obtains the Lower Heating Value (LHV) or net specific heat. The last quality is normally used for practical purposes, since the latent heat of vaporisation is not recovered. The heating value of household waste is relatively low compared to other common combustibles. The reason has to be found in the high percentage of humidity and inerts. The following table compares the heating value of different combustibles: As a consequence of the strong heterogeneity of waste, the average heating value can be determined only based on the waste composition and the heating value of the single components. The average heating value nowadays for municipal waste lays around 7900 kJ/kg , since the paper/carton fraction is about a quarter of the total in weight.

Determination of waste heating value based on ultimate analysis

In the past many methods have been investigated to ascertain the waste heating value given its proximate composition. One of the first equations is found in [24] and it is based on the

Combustible	kJ/Kg
Household waste	5000-10000
Household-like waste from commercial activities	8000-12000
Wood	16000
Wood coal briquettes	18000
Coke Coal	35000

Table 2.2: Heating value of different fuels.

assumption that, in absence of humidity, the waste shows the same heating value of dry wood.

$$LHV[kJ/kg] = 1929y_B - 2514y_w \quad (2.2)$$

where y_B is the fraction of combustibles and y_w the one of water. From this formula in fact, for a combustible with no ashes and no humidity, the heating values results equal to 19260 kJ/kg , a value that corresponds to the one for dry wood (circa 19222 kJ/kg). This shouldn't surprise if we consider that the percentage of paper and carton makes about 30-35 % of the waste. The paper and carton heating value, with an average value of 10900/14483 kJ/kg are inferior to the one of wood, but this is compensated by the much higher heating value (in the range 19200/26922 kJ/kg) of plastic matters, which are represented in a percentage between 4,51 % and 8,5%. A similar value is obtained using the formula from Carre' et al. [25],

$$LHV_{wet} = 18800 \frac{100 - s}{100 + h} - 2454 \frac{h}{100 + h} \quad (2.3)$$

Where h , s is the percentage of moisture content and ash respectively on dry basis. A recent study [13] presents a new formula for obtaining the Higher Heating value based on the proximate analysis, as:

$$HHV[Mj/kg] = 0.3536FC + 0.1559VM - 0.078ASH \quad (2.4)$$

being FC the combustible fraction, VM the volatile matter and ASH the ash plus inerts fraction.

Determination of waste heating value based on proximate analysis

Many more relations exist to determine the waste heating value given the chemical composition of the waste. Some of these equations were originally used for estimating the heat of combustion of coal, such as the well-known Dulong's formula

$$HHV = 33950C - 144200(H - O/8) + 9400S \quad (2.5)$$

The three heating value estimation relationships that follow were developed to estimate the heat of combustion of the combustible fraction of industrial and municipal wastes on a moisture ash free basis. The following relationships are all expressed in *kcal/kg*. Chang equation

$$HHV = 8561.1 + 179.72H - 63.89S - 111.17O - 90.00Cl - 66.94N \quad (2.6)$$

Modified Dulong equation

$$HHV = 78.31C - 359.32(H - O/8) - 22.12S + 11.87O + 5.78N \quad (2.7)$$

Vondracek equation

$$HHV(as\,fired) = C(89.17 - 0.0622C_1) + 270(H - O/10) + 25S \quad (2.8)$$

For the Vondracek's equation, C_1 is the carbon content on a moisture and ash-free basis and C , H , O and S are the percents of the elements on a as-fired (wet) basis.

Ash Fusion Characteristics

The ash melting point is a waste property that often limits the burning rate on hearts and grates. Ash fusion is a fearsome matter in fluid bed furnaces where continued operation of the system depends on maintaining dry bed grains. As a consequence of the importance of ash fusion temperature, the prediction of the onset of slagging (fusion of the ash) and fouling (accumulation of fused deposit) has been and remains an important concern to fuels technologists. Since ash contains seven major and numerous minor constituents in several hundred different mineral compositions and crystal forms, analysis of the problem and formulation of reliable prediction tools is difficult. In the course of burning off the combustible matter, the mineral matter in coal is converted into oxides. These oxides are principally SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , Na_2O and K_2O . In the case of coal TiO_2 and P_2O_5 are also present, but in small quantities. For biological sludge P_2O_5 can be over 10% of the ash and refuse phosphorous is variable, but usually less than 5%. Often, the SO_3 content of ashes is reported since, under the ASTM ashing procedure, the alkaline earth and alkali metal oxides capture SO_3 . These sulfates decompose above 1000 °C and, therefore, analytical data used for prediction of ash melting behaviour should be normalized to a sulphur-free basis.

Chapter 3

Process description

Waste can be disposed of in a variety of way, amongst which incineration plays a very important role. For bulky solids, highly combustible wastes or wastes with high water content, incineration offers a significant volume reduction and provides detoxification for combustible carcinogens, pathologically contaminated materials, toxic organic compounds or biologically active materials that would affect sewage treatment plants. Incineration mitigates the environmental impact for organic material that would leach from landfills or create odor nuisances. In addition the impact of the greenhouse gas generated in incinerating solid waste is less than that of the methane generated by landfilling operations. Also, because of strict air pollution emission requirements applicable to municipal refuse incinerators, the criteria for pollutant air emissions per kilowatt-hour produced are significantly less than that generated by the coal- and oil-burning utility plants whose electricity production is substituted by waste to energy facilities.

Energy recovery is important when large quantities of waste are available and reliable markets for by-product fuel, steam or electricity are nearby. In EU countries, energy recovery is legally required for plants built after 2005, [7]. Incineration forms oxides or glassy, sintered residues that are insoluble. The ashes so obtained can be then disposed in a landfill without any problem of biodegradation of organic material leading to subsidence and gas formation that disrupts cell-capping structures, or leaching, with potential contamination of the underground water [23].

In this chapter we have a closer look at the incineration process and at some state of art incinerator building concepts. A different plant layout affects in fact greatly the model structure, as the same processes happen at different time for different types of incineration plant. The incineration process from the chemical and thermo-dynamical point of view is treated in details

in Chapter 4. The two most commonly used types of waste incinerators of untreated waste for medium/great potentiality are the rotary kilns and the incineration on heart/grate. In general most small-scale incineration plants use a stationary hearth or a static grate to support the waste, while larger plants use moving grates or rollers, to mix the refuse while moving it across the furnace. All through the report we will only consider combustion on moving grates. For an overview of the various incineration plant types we remit to [26].

3.1 How an MSW Incineration plant works.

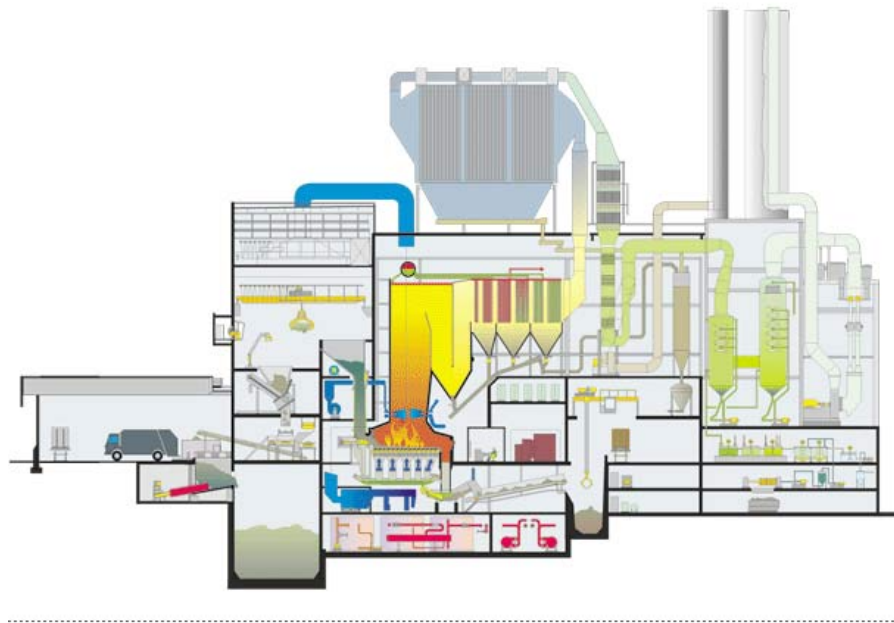


Figure 3.1: Municipal Solid Waste incineration plant [3]

The waste is conveyed by trucks or train and stored in the waste bunker or waste pit. From there it is fed to the feeding system with a crane. The feeding system, comprising the crane, funnel and feeder ram, moves the waste onto the grates where it will be burnt. The necessary combustion air is blown in a cross-countered or bevelling flow through the grate. Thus the waste is dried and burned in three process steps (drying, pyrolysis and char combustion) and the ash finally sintered, Figure 3.2. Additionally secondary air is injected above the bed to ensure complete combustion of the gaseous products. These processes are described in detail in Chapter 4. The three main processes take place thanks to the combustion zone above the grate bed that provides the heat to start and in part maintain the reactions. As described in Chapter

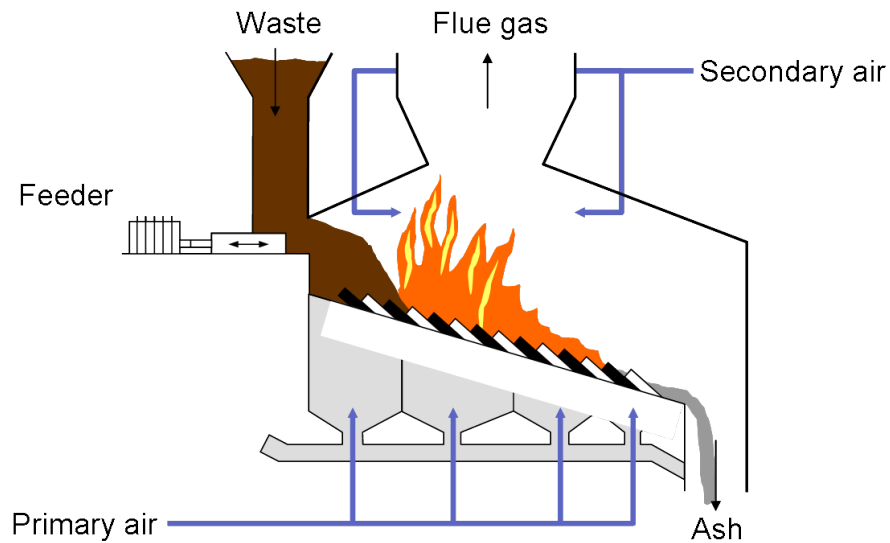


Figure 3.2: Scheme of a combustion bed with grates. The blue arrows represent the primary and secondary air. The waste, in brown, is loaded in the funnel via a crane and pushed on the grate with a stocker. The moving grate bars ensure transportation of the waste on the grate, at the end of which the ashes are discharged into the ash bunker.

4 the three processes are strictly interconnected and can only be controlled conditionally. The type and possibilities of the regulation interference into the processes are determined in crucial measure by the grate construction [23]. The main and most important precondition for the operation of an incineration plant with low emission is a combustion air supply defined at every time and in every place. For grate systems, primary air (or underfire air) is defined as the air supplied under the grate surface through several independent plenums to provide a proper distribution of air addition along the combustion path. Independently from the grate type, the oxygen supply for combustion comes with the primary air, supplied in five to six separated zones in the grate length direction of the waste bed. In the width sense each grate zone is supplied with air on its entire surface. To keep the waste layer thickness as constant as possible and to reduce fluctuations in the air flows, which would cause an increased carry-through of ashes from the combustion bed, the grates bars are posed with a very high resistance (about 1000 Pa) on the air side. In comparison the resistance offered by the waste layer is about 300 Pa. Secondary air may be admitted trough high velocity jets in the sidewalls and roofs of the furnace enclosure. While the solid residue, such as ashes are collected at the end of the grates (ash discharge), the gasses pass trough the steam generation section to then be treated in the flue gas cleaning section.

3.1.1 Heat recovery steam generators

While in conventional power plants energy production is the main goal, in waste to energy plants the disposal of the waste is in the foreground. The waste must be first of all inertized and the organic pollutants destroyed. Energy conversion in this case is only a positive byproduct. As a consequence Waste to Energy plants are often not conducted in a way to maximize energy production. During combustion the chemical energy bound in the fuel is released and converted in the thermal energy of the hot flue gasses and in radiation energy from the flame. To use this energy, heat exchange surfaces are positioned in the combustion chamber and in the flue gas path; water or water steam flows through these heat exchangers, as heat transfer media. Preheated water is pumped from the feedwater tank via a feedwater pump, in the boiler. The boiler is under pressure and in it the water is brought to boiling point. The steam so generated is separated from the water in a drum and proceeds to the superheater. The saturated steam entering the superheater has a specified, pressure dependant temperature, the so-called saturation temperature. At the exit of the superheater we have superheated steam (Figure 3.3, Point 3). In waste to energy plants the common steam parameters are 40 bar pressure and 400°C temperature. The superheated steam is then expanded in steam turbine, which drives a generator. The pressurized steam expands until a vacuum of 0.05 to 0.08 bars to maximize the enthalpy difference. This maximizes the turbine pressure ratio and therefore the turbine power output. The vacuum in the condenser is obtained subtracting heat from the incoming steam via water or air-cooling. The steam condenses, reducing its specific volume; in this way the condensate is evacuated (Figure 3.3, Point 2). The condensate is then pumped back in the feedwater tank (Figure 3.3, Point 2).

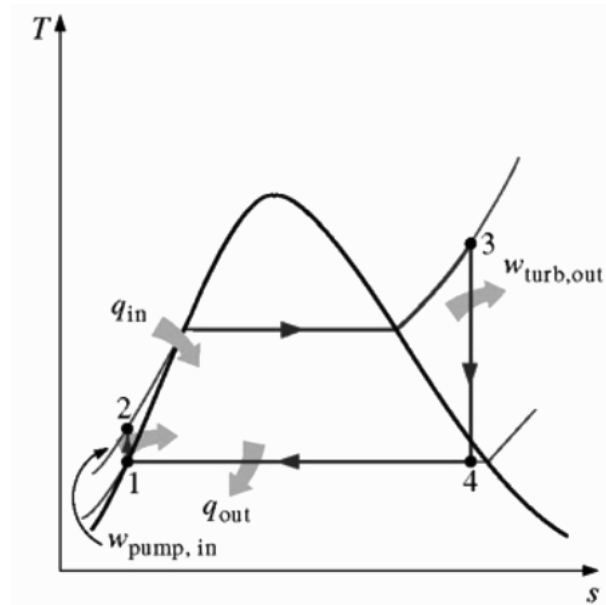


Figure 3.3: Schematic representation of a Rankine Cycle with heat and work fluxes.

The gas cleaning zone, see Figure 3.1, including the electrostatic precipitators, is more than one third in size of the total plant.

Chapter 4

Thermal and chemical processes

The waste, characterized as in Chapter 2, undergoes several thermo-chemical processes during its residence in the incineration plant. These processes are described in this chapter; their understanding is needed to develop the model described in Chapter 5, that is later used to define and test the control approached described in Chapter 7 and Chapter 8.

The combustion process involves drying, pyrolysis, gasification, and char burn-out; the ashes undergo ash sintering. Although these processes are not clearly separated on the grate, their temporal sequence can be schematized as drying, pyrolysis, gasification, char combustion and ash sintering. At steady state operations, these processes simultaneously take place in consecutive zones of the grate.

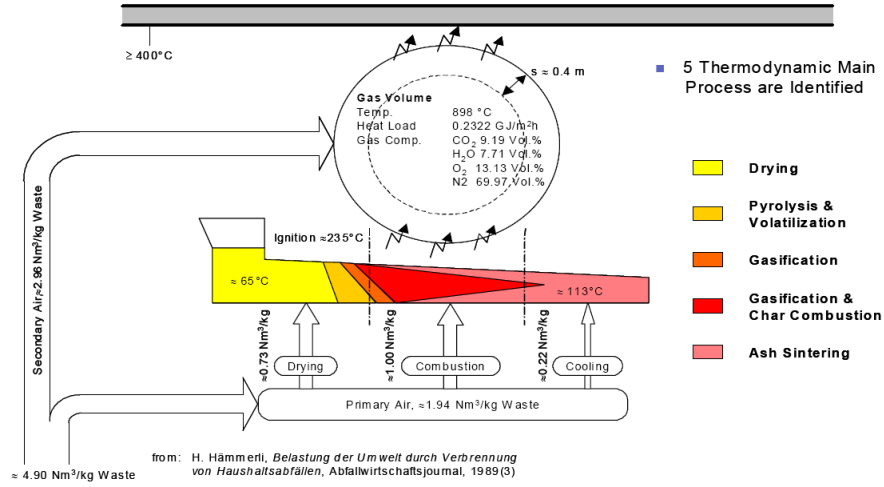


Figure 4.1: Spatial progression of combustion on the waste bed.

4.1 Drying

The drying zone is of prime importance for a correct waste incineration process since it influences the location of the flame on the grate. To ensure a homogeneous temperature distribution in the furnace and to guarantee the required residence time of the flue gases and reduce the material stress of the grate, the combustion should not start too early or finish too late. The drying process is strictly connected with the heat transfer in the waste bed. Chapter 3 reports a short description of the three heat transfer types. For a more detailed description we direct to the widely available literature, such as [27], [28].

In a quasi-homogeneous bulk streamed by a fluid, such as the waste bed on the grates, the heat transfer process is given by the sum of the contribution of the convective heat transfer between gas and particles, the incoming radiation from the combustion zone and the heat conduction at the contact point between two particles. The effective heat transfer coefficient in such a bulk is given by the relation:

$$h_{eff,0} = h_{Conduction} + h_{Radiation} + h_{Convection} \quad (4.1)$$

where h is the heat transfer coefficient. The heat transfer coefficient is therefore a function of the fluid velocity and its characteristics (heat capacity, density, heat conductivity, viscosity). How to determine the three contributions to the global heat transfer coefficient is the argument of the following paragraphs.

4.1.1 Convective Drying

In general, the convective heat transfer $\dot{Q}_c$ is given by the relation

$$\dot{Q}_c = hA(T_g - T_s) \quad (4.2)$$

where h is the convective heat transfer coefficient, A the concerned surface, T_g and T_s the gas and solid temperature, respectively. The convective heat transfer coefficient can be expressed as a function of the Reynolds number, Nusselt number and Prandtl number

$$\frac{h \cdot d_p}{k} = 1.17 Re^{0.585} \cdot Pr^{1/3} \quad (4.3)$$

$$Re = \frac{d_p \cdot \nu \cdot \rho}{\eta} \quad (4.4)$$

$$Nu = h \frac{d_p}{\kappa} \quad (4.5)$$

$$Pr = \frac{c_p \cdot \eta}{\kappa} \quad (4.6)$$

with:

d_p = waste particle diameter [m]

ν = air velocity in the waste bed [m/s]

h = convective heat transfer coefficient [W/m^2K]

ρ = air density [kg/m^3]

κ = air conductivity [$W/m, K$]

η = dynamic viscosity [$kg/m, s$]

c_p = specific heat at constant pressure [$J/kg, K$]

The equivalent diameter of the waste particles (diameter of a sphere with the same volume) is given by:

$$d_p = 2d_{waste} \cdot 3/4\pi^{1/3} \quad (4.7)$$

The convective heat transfer in a bulk presents itself, due to the changes in shape, much more complex than the air flow pattern when simpler bodies are involved (spheres, cylinders, etc). When a bulk is considered, as it is the case in the waste bed, the effect of voids has to be considered. An average Nusselt number has to be used, obtained scaling the Nusselt number for a pile of spheres by a factor f_ϵ . This factor accounts for the voids and the irregularity in shape of the waste particles, which increase the turbulent effects.

$$Nu_{bulk} = f_\epsilon Nu_{sphere} \quad (4.8)$$

$$f_\epsilon = 1 + 1.5(1 - \epsilon) \quad (4.9)$$

The convective heat transfer on the grate can then be calculated using the Nusselt number and the logarithmic mean temperature, as

$$\dot{Q}_{conv} = \kappa \eta_p A_p \Delta \Theta_{log} \quad (4.10)$$

where the logarithmic mean temperature is defined as

$$\Theta_{log} = \frac{T_{g,e} - T_{g,a}}{\log \frac{T_{g,e} - T_p}{T_{g,a} - T_p}} \quad (4.11)$$

η_p is the number of particles and A_p is the particle surface. The mass transfer due to convection can be modelled in analogy to the heat transfer ([27], [11]), with the Sherwood number and the Schmidt number replacing Nusselt and Prandtl. Generically, it can be written

$$\frac{Nu}{Sh} = \frac{C_1 Re^m Pr^n}{C_1 Re^m Sc^n} \quad (4.12)$$

being Sc the Schmidt number and Sh the Sherwood number, defined as

$$Sc = \frac{\eta}{\rho \cdot D_{H_2O}} \quad (4.13)$$

$$Sh = k_g \cdot \frac{L_c}{D_{H_2O}} \quad (4.14)$$

D_{H_2O} is the mass diffusion coefficient of water in m^2/s and L_c is the characteristic dimension. Even in this case we use an average Schmidt number, to take into account the additional turbulences due to the voids and irregular shapes $Sh_{bulk} = f_\epsilon Sh_{sphere}$. The convective mass transfer in a bulk can be therefore written, in analogy to the heat transfer, as

$$\dot{m} = A \cdot k_g (P_{svp} - PP) \quad (4.15)$$

Where P_{svp} is the saturated vapour pressure dependent on the waste temperature and calculated from standard steam tables and PP is the vapour partial pressure. While drying the waste is not only streamed through by pure air but by a mixture of air, water and pyrolysis gases, which are generated at locations where the local content of water is already evaporated. There the waste is heated up to temperatures where volatile organic compounds are gasified and at further temperature increase pyrolysis might start.

4.1.2 Radiative Drying

The radiative drying is caused by the radiative heat transfer between the reaction zone above the waste bed, the bed itself and the furnace walls. Heat fluxes between different surfaces are modelled according to the Stefan-Boltzmann theory according to which the emissive power of an ideal black body is a function of temperature only. Based on experiments, Josef Stefan suggested in 1879 that the total emissive power of a black body is proportional to the fourth power of the absolute temperature. Later, Ludwig Boltzmann applied the principles of classic thermodynamics and analytically derived the same fact. Thus the following dependence of E on T is called the Stefan-Boltzmann Law.

$$E = \sigma T^4 \quad (4.16)$$

where σ is the Stefan-Boltzmann constant. The temperature of the black surface is the absolute temperature. One should note that the emissive power is spectral in nature (being different at different wavelengths). For black bodies (which absorb and emit fully at all wavelengths) this is unimportant. For solids, liquids and gases that absorb or emit preferentially in one or more spectral regions (importantly including carbon dioxide and water vapour), however, the spectral characteristic of both emitter and absorber must be taken into account. To simplify computation, the concept of a grey body has been developed. At the same temperature, the total emissivity of a grey body is somewhat less than a black body. The ratio of emissive power of a grey body to the black body at the same temperature is known as emissivity. If $E_\lambda(\lambda, T)$ represents the hemispherical monochromatic emissive power of a non black (grey) surface maintained at temperature T and measured at a particular wavelength λ , then the hemispherical monochromatic emissivity is defined as the ratio of $E_\lambda(\lambda, T)$ to the hemispherical monochromatic emissive power of a black body at the same temperature $E_{b\lambda}(\lambda, T)$

$$\epsilon(\lambda, T) = \frac{E_\lambda(\lambda, T)}{E_{b\lambda}(\lambda, T)} \quad (4.17)$$

Most real surfaces exhibit the characteristics of a selective emitter, in that ϵ_λ are different for different wavelengths of the emitted energy, and may be dependent on the surface temperature. The hemispherical total emissivity is defined as

$$\epsilon(T) = \frac{E(T)}{E_b(T)} \quad (4.18)$$

so that the emissive power of non black (grey) surfaces is readily calculated when ϵ is known $E = \epsilon\sigma T^4$. Radiation follows straight lines, thus the geometrical relationship between surfaces

and volumes has a direct impact on the next flux. Also, surfaces absorb and reradiate and may reflect heat, thus compounding the difficulty of the analysis. Considering the case of two parallel surfaces, the heat flux between them can be obtained as

$$q_{ij} = \frac{\sigma (T_i^4 - T_j^4)}{\left(\frac{1}{\epsilon_i}\right) + \left(\frac{1}{\epsilon_j}\right) - 1} \quad (4.19)$$

Being $\epsilon_{i,j}$ the surface emissivities. The waste emissivity is not a constant but is given as a function of the proximate analysis in the pile. The more the ash, the lower the waste emissivity.

$$\epsilon = \epsilon_{daf}m_{daf} + \epsilon_{water}m_{water} + \epsilon_{ash}m_{ash} \quad (4.20)$$

The total emissivity of the flames is a superposition of the contribution from the soot particles and the gases. In order to calculate the total emissivity of the flames one has to determine the effect of mutual absorption of the radiation from the gases and soot. Tien et al. (1972) give a simple formula to calculate the total emissivity ϵ_t when both soot emissivity ϵ_s and gas emissivity ϵ_g are known. This formula is

$$\epsilon_t = \epsilon_g + \epsilon_s - \epsilon_s\epsilon_g \quad (4.21)$$

The emissivity of the soot particles ϵ_s is dependent on two quantities, the flame height and the volume fraction of the soot particles in the flames. Using the work of Felske and Tien (1973) to calculate the emissivity of the soot a value between 0.025 and 0.036 for a fire power between 3 kW and 8 kW has been found [29]. As for the flame emissivity, of the gases commonly present in a fire, only CO_2 and H_2O contribute to the emissivity. The other gases (O_2 and N_2) consist of symmetrical molecules that emit and absorb radiation only at much higher temperatures.

The temperature increase in the waste due to the heat transfer by radiation leads to the evaporation of the humidity contained in the waste. The amount of evaporated water can be obtained simply by calculating the heat balance, given equation 4.19 as:

$$\dot{m}_v = \frac{\dot{Q}}{l_{evap}} = \frac{\sum q_{ij}}{l_{evap}} \quad (4.22)$$

with

$\dot{m}_v$ =rate of vaporized water in [kg/s]

$\dot{Q}$ =radiative heat flux in [kJ/s]

l_{evap} = water latent heat of vaporization = 2261 [kJ/kg]

4.1.3 Conductive Heat Transfer

For one-dimensional heat transfer by conduction in the x -direction, the heat transfer rate per unit area is given by

$$\dot{Q}_a = -\lambda \frac{dT}{dx}, \quad (4.23)$$

where λ is the thermal conductivity and $\frac{dT}{dx}$ is the thermal gradient. The minus sign acknowledges the fact that the heat flow in the positive direction x requires a decline in temperature with increasing x . For steady, one-dimensional conduction in isotropic solids, the thermal gradient is linear and Equation 4.23 becomes

$$\dot{Q}_a = -\lambda \frac{\Delta T}{\Delta x}, \quad (4.24)$$

where Δx is the thickness of the slab and ΔT the surface-to-surface temperature difference. Conductive heat transfer in waste, which is an anisotropic solid, can be calculated using the superimposition principle. Waste can be seen as an horizontal and transversal heap of different solids and gas (water, combustibles, inerts and the gas contained in the pores). The equiv-

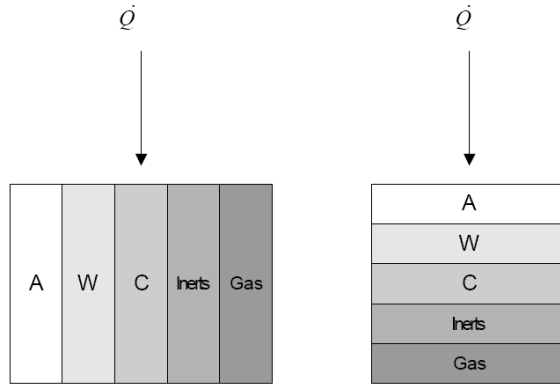


Figure 4.2: Superimposition principle for parallel and series configuration

alent heat conductivity can therefore be calculated, for an horizontal and a transversal pile, respectively as

$$\lambda_H = \frac{1}{x_C/\lambda_C + x_W/\lambda_W + x_A/\lambda_A + x_{inerts}/\lambda_{inerts} + x_G/\lambda_G}, \quad (4.25)$$

$$\lambda_T = x_C\lambda_C + x_W\lambda_W + x_A\lambda_A + x_{inerts}\lambda_{inerts} + x_G\lambda_G, \quad (4.26)$$

with i = combustibles, water, ash, inerts and gas. In the first case the single heat conductivity are laid in parallel, while in the second case they are laid in series. x_C , x_W , x_A , x_{inerts} and

x_G are the thickness of the equivalent "slab" of each component. The layer thickness can be obtained as

$$x_i = (1 - \epsilon_p) \cdot \frac{y_i/\rho_i}{\sum y_i/\rho_i}, \quad (4.27)$$

with i = combustibles, water, ash, inerts, while the equivalent thickness of the gas slab is simply the porosity diameter ϵ_p , that means $x_G = \epsilon_p$. The waste components' heat conductivity are reported in the table 4.1.3, while the one for the gas is a function of the gas composition and

Substance	Combustible	Water	Ashes	Inerts
$\lambda = \frac{W}{m,K}$	0,20	0,64	0,57	15,00

Table 4.1: Heat conductivity for waste components [2].

temperature.

4.2 Pyrolysis and gasification

When all the water in the waste is evaporated, the temperature of the waste increases. As soon as the waste temperature reaches a certain value, first the gasification of volatiles and shortly later also the pyrolysis start. Pyrolysis occurs in the absence of oxygen when higher hydrocarbons are cracked into smaller ones at increased temperature levels. Therefore the primary airflow through the waste bed is maintained at an understoichiometric level. To start the pyrolysis the waste is heated up to a temperature, where the oxygen reacts with some of the volatile hydrocarbons and solid components in exothermic reactions. The heat release of these reactions supplies the energy to run the pyrolysis, but since most of the oxygen is consumed by the initial reaction there is almost nothing left to oxidize the newly gasified hydrocarbons. Thus, a mixture of gasified hydrocarbons, water from the reaction of oxygen and hydrogen, and remaining nitrogen leaves the waste bed and becomes the fuel gas for the homogeneous secondary combustion above the waste bed. The final composition of the pyrolysis gases and the volatilisation ratio depend on the composition and the temperature of the waste and the residence time of the hot gas in the waste bed. The thermal decomposition or pyrolysis of waste solids in the absence of air or in limited air supply occurs in most burning systems. Both physical and chemical changes occur in solids undergoing pyrolysis. The most important physical change in materials such as bituminous coal and some plastics is a softening effect resulting in a plastic mass, followed by a resolidification. Cellulosic materials increase in porosity and swells as volatiles are evolved. As cellulose pyrolysis begins (at about 200 °C),

complex, partially oxidized tars are evolved. As the temperature increases, these products further decompose or crack, forming simpler, more hydrogen rich gaseous compounds and solid carbon. The solid residue approaches graphitic carbon in chemical composition and physical structure and it is normally referred to as char. The rate-controlling step in pyrolysis is the rate of heat transfer into the waste or the pyrolysis reaction rate. It is dependant upon the temperature and the physical dimension of the waste. Below 500 °C, the pyrolysis reactions appear rate-controlling for waste pieces smaller than 1 cm in size. Above 500 °C, pyrolysis reactions proceed rapidly, and heat transfer and product diffusion are rate limiting. For large pieces (greater than 5 cm), heat transfer probably dominates for all temperatures of practical interest. The upper temperature limit for pyrolysis weight loss is a function of then material being heated. For bituminous coal the weight loss achieved at 950 °C is about as high as it will be achieved at any practical temperature. Cellulose pyrolysis is essentially completed between 575 °C and 700 °C. The time required for pyrolysis of solid waste can be estimated by assuming that the rate is controlled by the rate of heating.

4.2.1 Liquid Products

The liquid products of pyrolysis is known to contain a complex mixture of alcohols, oils and tars known as pyroligneous acids. Pyrolysate liquids from municipal refuse contains from 70 to 80% water with the remainder being a wide range of (often oxygenated) organic compounds [5].

4.2.2 Gaseous Products

The yields, composition and calorific value of gaseous pyrolysates depend upon the type of material, the heating rate, and the ultimate temperature. Figure 4.2 shows that for typical refuse components, gas yields ranges from 17% to 31% of the air-dried fuel.

4.2.3 Thermal decomposition kinetics

Although the details of the complex chemistry and heat transfer processes controlling pyrolysis reactions in wastes (thick sections, often compounded of several materials, anisotropic and heterogeneous in thermal and chemical properties) are not known, pyrolysis has been extensively studied for wood and synthetic polymers. In the model described in Chapter 5 the approach adopted in evaluating the kinetic parameters for the pyrolysis of biomass is to assume a first order rate of reaction with respect to the amount of undecomposed material in the solid and the temperature [5], [30], [31]. The volatilization rate k_{vol} [s^{-1}] can be interpreted as a pseudo

Components	Gas	Water	Other Liquid	Char (Ash-free)	Ash
Cord hardwood	17.30	30.93	20.80	29.54	0.43
Rubber	17.29	3.91	42.45	27.50	8.85
White Pine Sawdust	20.41	32.78	24.50	22.17	0.14
Balsam Spruce	29.98	21.03	28.61	17.31	3.07
Hardwood leaf mixture	22.29	31.87	12.27	29.75	3.82
Newspaper I	25.82	33.92	10.15	28.68	1.43
Newspaper II	29.30	31.36	10.80	27.11	1.43
Corrugated Box paper	26.32	35.93	5.79	26.90	5.06
Brown Paper	20.89	43.10	2.88	32.12	1.01
Magazine Paper I	19.53	25.94	10.84	21.22	22.47
Magazine Paper II	21.96	25.91	10.17	19.49	22.47
Lawn grass	26.15	24.73	11.46	31.47	6.19
Citrus fruit Waste	31.21	29.99	17.50	18.12	3.18
Vegetable Food Waste	27.55	27.15	20.24	20.17	4.89
Mean Values	24.25	23.50	22.67	24.72	11.30

Table 4.2: Yields of pyrolysis products from different refuse components [5].

reaction rate and therefore can be determined by means of an Arrhenius equation.

$$k_{vol} = k_0 \cdot \exp\left(-\frac{E_a}{RT}\right) \quad (4.28)$$

$$\dot{m}_{vol} = -k_{vol} (m - m_f) \quad (4.29)$$

with:

T =temperature of the waste in $[K]$

$\dot{m}_{vol}$ =volatilisation rate in $[kg/s]$

m =initial waste mass in $[kg]$

m_f =mass of volatile components in the waste in $[kg]$

The values for the pseudo activation energy ($E_a = 8700 \text{ Kj/kmol}$) and the frequency factor ($k_0 = 8 \cdot 10^5 \text{ s}^{-1}$) are taken from [25].

4.2.4 Gasification reactions

In the process of gasification the biomass reacts with oxygen to produce a gas mixture mainly of carbon monoxide (CO) and hydrogen (H_2O). In the combustion process instead, the biomass reacts with oxygen to produce mainly carbon dioxide (CO_2) and water (H_2O). The gasification differs from combustion in the air fuel ratio applied to the process. In the combustion the biomass is converted into heat and inert gases while in the gasification is converted into a gas carrier of chemical energy. These gases further combust when enough oxygen is available.

Studies [5] of the off-gas from beds of burning refuse in a municipal incinerator have confirmed that the off-gas composition is controlled by the water-gas shift equilibrium



The equilibrium constant is calculated given the Gibbs free energy at $298K$, corrected to the process temperature:

$$K_p = \exp\left(-\frac{\Delta G_R^\Phi(T)}{R \cdot T}\right) = \exp\left(\frac{\Delta S^\Phi}{R} - \frac{\Delta H^\Phi}{RT}\right), \quad (4.31)$$

$$\Delta S^\Phi = \Delta S_0^\Phi + \int \frac{c_p(T)}{T} dt, \quad (4.32)$$

$$\Delta H^\Phi = H_0^\Phi + \int c_p(T) dt, \quad (4.33)$$

with:

K_p =Equilibrium constant at constant pressure

ΔG_R^Φ =free Gibbs energy in $[KJ]$

T =Temperature $[K]$

S =Entropy $[KJ/(kmol, K)]$

H =Enthalpy $[KJ/kmol]$

4.3 Char Combustion

Char combustion is described relatively at the combustion of a carbon sphere. The topic of combustion of a carbon sphere is in fact important because all pyrolyzing solids, once completely charred, are attacked by oxygen in much the same manner as carbon [5]. The rate of burning of any fuel is strongly influenced by the heat flux incident upon the fuel surface. In the case of a simple solid, reaction takes place at its surface, whereas in the case of a liquid or a pyrolyzing solid it takes place in the gas phase. Consequently the case of combustion of pyrolyzing solids requires a detailed understanding of both the internal (solid phase) and external (gas phase) heat and species conservation. Once all the volatiles are expelled the carbonaceous residue

of a pyrolyzing solid behave in the same manner as a simple solid [5]. The combustion of a carbon particle is accompanied by high surface temperature at which it becomes incandescent. Oxygen diffuses from the free stream to the surfaces where it directly reacts with the solid to release a great quantity of heat. Much of the heat is lost to the surroundings by radiation. It is reasonable to expect that, whereas the burning rate of liquid fuels and pyrolyzing fuels strongly depends on the rate of heat transfer to the fuel surface, that of simple solids depends strongly upon the rate at which the oxygen diffuses to the fuel surface. Any heterogeneous reaction involves the following five steps in series.

1. Oxygen has to diffuse to the fuel surface
2. Diffused oxygen has to be absorbed by the surface
3. Absorbed oxygen has to react with the solid to form absorbed products
4. Absorbed products have to be desorbed from the surface
5. Desorbed products have to diffuse away from the surface

Since these steps occur in series, the slowest of them determines the burning rate. In the case of carbon combustion steps 2 and 4 are known to be extremely fast. When the temperature is low, the particle is small and the flow around is feeble, step 3 is known to be much slower than step 1 or step 5. The burning rate is determined by the chemical kinetics and therefore the process is kinetically controlled. In kinetically controlled processes the burning rate depends upon temperature exponentially. Since the process of diffusion is a function of particle size and flow, and since it is irrelevant in the kinetic regime, the burning rate is independent of the particle size and flow around it. The concentration of oxygen at the reacting surface is not too different from the free stream concentration. On the other hand, when the particle and flow velocity are large and temperature is high, step 3 is known to be much faster than step 1 or step 5. The burning rate is then controlled by the diffusion rate of oxygen to the particle. In the diffusionally controlled regime the burning rate depends weakly on the temperature and strongly on the particle size. The oxygen concentration at the reacting surface is negligibly small. Carbon and metal combustion are predominantly diffusion controlled, since at the low temperatures required to bring about the kinetic control, the particle lose so much heat so rapidly that extinction occurs.

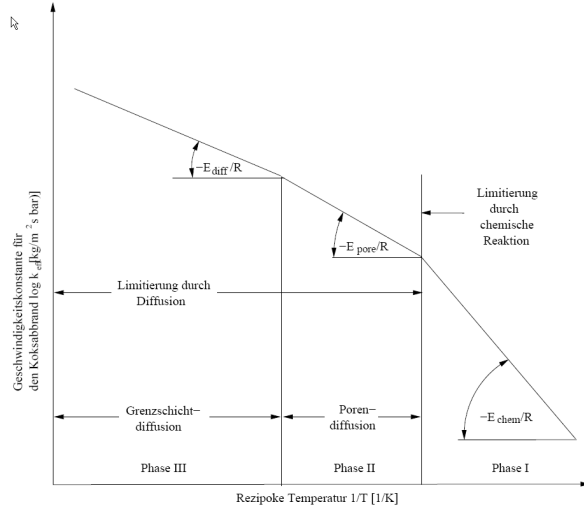


Figure 4.3: Temperature dependence of coke combustion in the Arrhenius diagram [2]

4.3.1 Diffusional Combustion

Diffusional combustion of a carbon sphere depends upon the extra variable of stoichiometry. Firstly, at moderately high temperatures oxygen diffuses to the carbon surface and reaction occurs to form CO_2 ,



The fuel/oxygen ratio for this mechanism is 12/32. The product CO_2 diffuses away from the surface. Secondly, when there is no free oxygen present, the reaction between O_2 and carbon at the surface might yield a richer oxide, that means, CO instead of CO_2 ,



The stoichiometric fuel ratio for this mechanism is naturally higher, $f = 12/16$. Moreover carbon can also react with the CO_2 with the so-called Boudouard reaction [2], [1]



The diffusional burning rate is given as:

$$k_{diff} = \frac{12Sh\Phi D_o}{Rd_p T_m} \cdot \left(\frac{T}{T_o}\right)^{1.75} \quad (4.37)$$

with $D = D_o \left(\frac{T}{T_o}\right)^{1.75}$ = diffusivity

$Sh = 2 + 0.654Re^{1/2}Sc^{1/3}$ = Sherwood number

Φ gives the relation between formed CO and formed CO_2 , as follows from [32], [2], [33].

$$\Phi = \frac{CO}{CO_2} = A \cdot \exp\left(-\frac{B}{RT_p}\right) \quad (4.38)$$

$$C + \frac{1}{\Phi}O_2 \rightarrow 2 \cdot \left(1 - \frac{1}{\Phi}\right) \cdot CO + \left(\frac{2}{\Phi} - 1\right) CO_2 \quad (4.39)$$

with

$$\Phi_{CO} = 2 \left(1 - \frac{1}{\Phi}\right) \Phi_{CO_2} = \left(\frac{2}{\Phi} - 1\right) \quad (4.40)$$

With $\Phi = 1$ only CO_2 is produced, while with $\Phi = 2$ the heterogeneous combustion results in only CO .

4.3.2 Kinetic Burning Rate

The kinetic burning rate k_{chem} is calculated using the standard Arrhenius equation:

$$k_{chem} = Ae^{-\frac{E}{RT}} \quad (4.41)$$

Values for A and E have been determined experimentally, and vary for different type of coal [6], [2].

4.3.3 Overall Burning Rate

The overall burning rate can then be calculated as

$$k_{eff} = \frac{1}{\frac{1}{k_{diff}} + \frac{1}{k_{chem}}}. \quad (4.42)$$

The burning rate of a char particle is then formulated as follows [31]:

$$\frac{dm}{dt} = -n_p A_s k_{eff} p_{O_2, \infty}. \quad (4.43)$$

In this equation A_s describes the specific reactive surface of the coke, including the pores surface. The reactive surface is in fact the sum of the external geometric surface A_p and the internal surface A_i . Moreover, $p_{O_2, \infty}$ is the oxygen partial pressure in the gas phase outside the boundary layer and n is the kinetic order of the reaction. As there are no available data for waste, we refer to studies for coal.

Investigation	Sample	T,K	$P_{O_2,\infty}$	n	E	A
Field et Al. (1967)	Carbon	950-1600	0.01-0.21	1	36	8700
Field (1969)	Sub-bituminous char	1300-2000	0.05-0.10	1	10-30	
Mulcahy and Smith (1971)	Anthracite char	1000-2300	0.20	1	15	
	Petroleum coke char	1000-2300	0.20	1	15	
	Bituminous char	1000-2300	0.20	1	15	
	Lignite char	1000-2300	0.20	1	15	
Smith (1970)	Anthracite char	1400-2200	0.20	1	19	19.3
Smith (1971)	Petroleum coke	1200-2270	0.20	1	18	20
	Anthracite char	1200-2270	0.20	1	17	10
	Bituminous char	1200-2270	0.20	1	16	8
Smith(1971)	Semi-Anthracite	1400-2200	0.1-0.2	1	19	20.4
Sergeant, Smith (1973)	Bituminous char	800-1700	0.15-0.20	1	27	
Hamor, Smith,Tyler (1973)	Lignite Char	900-2200	0.1-0.2	0.5	16	9.3

Table 4.3: Overall kinetic data for char combustion including corrections for boundary layer diffusion and surface exothermicity [6]

4.4 Ash Burnout

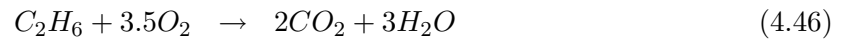
Municipal solid waste includes inert materials that cannot be destroyed in the combustion process. Also, the incineration process is inherently imperfect [5] so that some potentially combustible materials is dried, heated and carbonized but the desired next step (gasification of the char) is not achieved. Further some materials simply "falls between the cracks" (siftings) and leaves the hot combustion environment substantially unburned. These three components comprise bottom ash, the inevitable residue of municipal solid waste incineration operations. Municipal solid ash is usually characterized as :

- Bottom ash: the ash that falls from the grates combined with the siftings that fall through the grates
- Fly ash: the fine ash that becomes airborne in the primary chamber and either settles in the ducts and devices of the incinerator or ultimately becomes the inlet loading of particulate matter to the air pollution control system. Also, the fly ash includes refuse constituent that volatize in the high-temperature zones of the furnace and, subsequently, condense on particulate (often the small-diameter particles that present a large surface area). These constituents may include heavy metals and high molecular weight hydrocarbons with a significant health effect.

In the final part of the bed the grate bars move much slower and the bed starts rising up again. The residence time in the last zone of the furnace should be long enough to ensure the loss of incandescence for the ashes. The ashes are quenched and cooled down with water before they are transported to the slag bunker via a conveyor belt. The heat loss to the process caused by the ashes has, of course, to be considered in the overall heat balance of the process. From legal requirements [34] the mass fraction of unburned carbon in the ashes must not be higher than 2% of the total mass. Even if this constraints are of more environmental nature, the loss in chemical potential due to unburned carbon components has also to be considered in the heat balance.

4.5 Secondary Gas Reactions

The combustible gases that have been generated during the gasification and pyrolysis phase are leaving the waste bed with the primary air stream. As soon as this mixture of hydrocarbons, water vapour, nitrogen and remaining oxygen leaves the waste bed surface, it is ignited and burns in a homogeneous gas phase reaction. To assure complete combustion secondary air is injected into the combustion zone to maintain over-stoichiometric conditions. Thus, the stoichiometric coefficient of the secondary combustion zone is given by the amount of excess air. The oxygen that is needed for complete combustion is calculated from the total amount of air sent to the furnace and the remaining oxygen at the furnace exit. The compounds that react with air oxygen or with each other in the secondary combustion zone are water vapour from drying and previous reactions, methane, ethane, benzene and carbon monoxide. These compounds are assumed to react in the following reactions:



The final product amount can be obtained by imposing a reaction at equilibrium as previously described in 4.2.4.

Chapter 5

Process Modelling

The previous chapters deal with waste properties and the thermochemical processes in the waste combustion. This knowledge is the base for the model that is used in this study. The model needs to be detailed enough to ensure a correct response to a change in waste composition and operational conditions and correctly simulate the temperature profile in every zone of the bed but at the same time simple enough to test a control strategy on it with a reduced computational time. To generate a model suitable for the description of different plants with individual process concepts without any need to change major structural components we use a physical approach. The various processes and components are described using thermodynamic and chemical laws, avoiding the use of look-up tables based on measured data. All values and constants are taken from literature; all units are according to SI standard (meter, second, kilogram).

The model comprises the waste bed on the grate, the gaseous combustion above the grate and a simplified boiler. The simplest model unit for the waste bed is the so-called pile [4]; it can be seen as the volume of waste on a grate zone. Each pile is assumed to be homogeneous with regard to temperature and composition. Additionally the waste bed properties are considered to be constant all over the grate width. That means that, being x the axis along the waste movement, y the vertical axis and z the axis in the width direction, the waste properties vary in x and y but are constant in z . An upper layer is modelled, representing the thin layer of waste on top of the pile, subject to radiation from the above gas cloud, see Fig. 5.2. As the temperature of the upper layer rises, heat is transferred by convection into the lower layer. Each pile has as inputs the primary air flow (water, combustibles, oxygen, inerts), $f_p \in \mathbb{R}^4$ and its temperature T_p , the grate speed, V_g , the incoming waste feed rate (water, char, volatiles, inerts) $f_w \in \mathbb{R}^4$ and its temperature T_w . For the first pile the incoming waste is the waste from

the feeder, for the other piles it comes from the previous one.

The states for each pile are the lower layer mass in its four components (water, char, volatiles, inerts), $M_{LL} \in \mathbb{R}^4$, the lower layer average temperature, T_L , and the upper layer temperature T_u .

For the gaseous combustion model and the boiler there are also global inputs such as secondary air flow and its temperature and the energy input from auxiliary burners, $f_s \in \mathbb{R}^4$, T_s and Q , and states, as the gas cloud temperature, T_f , the flue gasses temperature at boiler exit, T_{GO} and the steam S .

The measured outputs are, in addition to the steam flow rate S , the residual oxygen O_2 the flame temperature T_f , the flue gas flow f_g and its temperature T_g and the height of waste pile h_w . From the equations described below we can directly prove the mass and energy conserva-

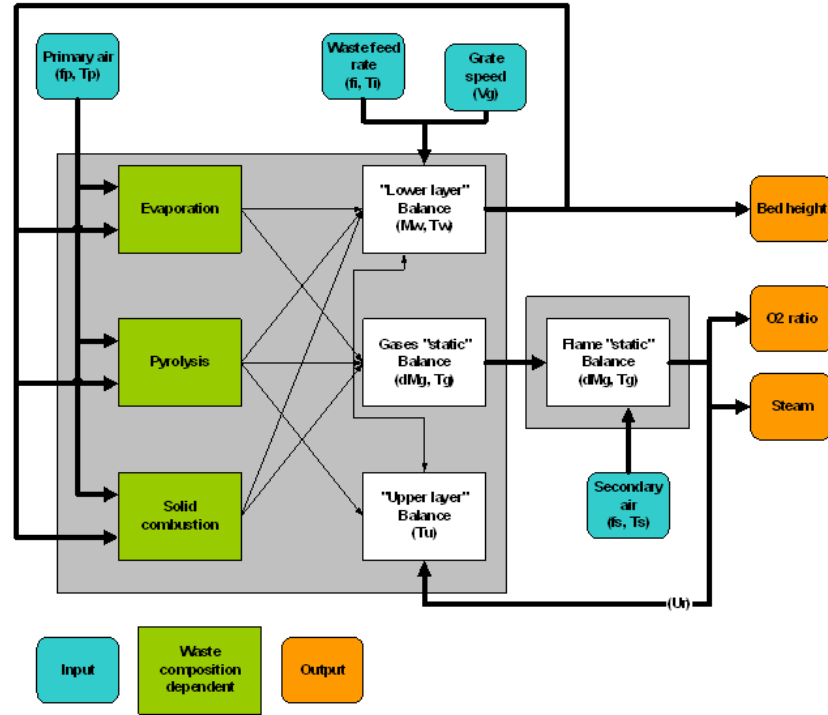


Figure 5.1: Model description. The picture shows inputs, outputs and dependencies between the process blocks [4]. The thermochemical processes, represented by green squares, are waste dependant, that means that they occur at a different time for different waste compositions. These processes are described by means of mass and energy balances, white squares

tion. In the model used in this research, four piles are laid in series, creating a so-called grate,

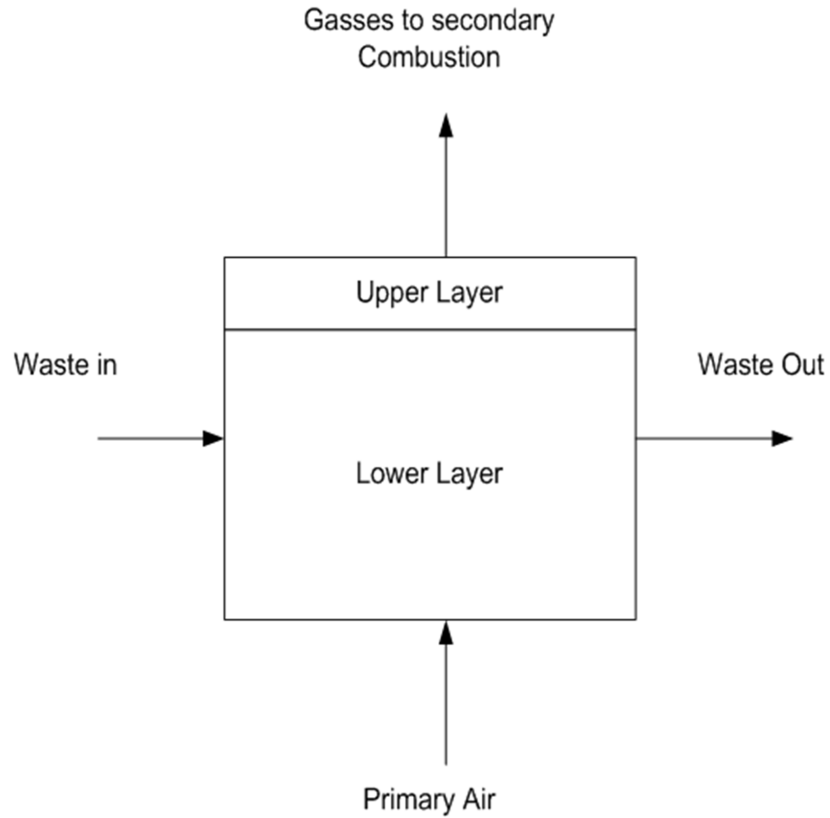


Figure 5.2: Schematic of a single pile. The pile is subdivided into a lower and upper layer, where the upper layer is meant as the superficial layer exchanging heat by radiation with the flame and walls. For modelling purposes only the heat balance for the upper layer is considered. The inputs to the system are primary air and incoming waste rate; the outputs are the outgoing waste rate and the primary combustion gasses.

see Fig. 5.3. Primary air is blown under each pile (from now on referred as zone), and each zone can be moved with a certain grate speed V_g . Mass transfer between adjacent piles occurs only in the x positive direction, that means, the backwards thrust effect is neglected.

On the first zone drying of the waste takes place, while on the second and third zone pyrolysis and glowing char combustion occur. The fourth zone is mainly used for ash burnout. Additionally, a fifth pile could be inserted, for complete ash cooling. The gasses thus produced are combusted in the combustion chamber above the bed where secondary air is injected. In the case of a Waste to Energy plant (incineration plant with energy recover) the combustion chamber is a standard boiler, as described in Chapter 3.

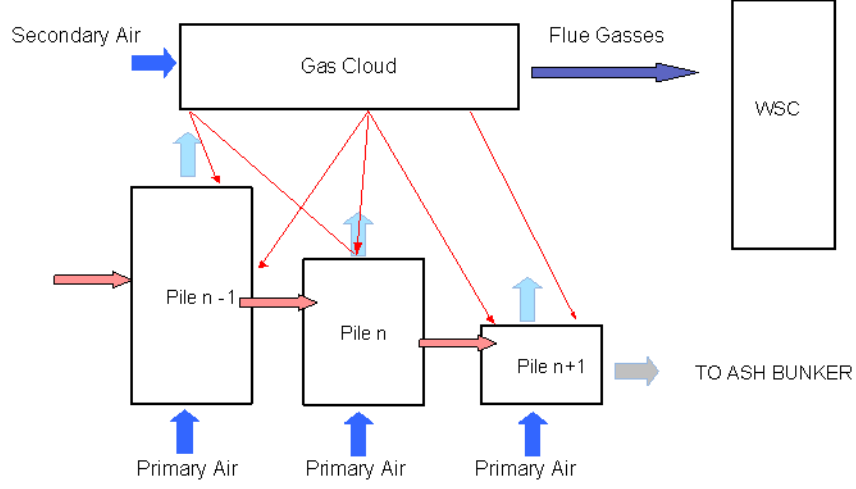


Figure 5.3: Schematic of a multiple piles configuration. The waste flows from Pile $n - 1$ to Pile $n + 1$, each pile has its own primary air flow; the secondary air is blown over the waste bed.

5.1 State Equations

The equations are of the kind

$$\dot{x} = f(x, u) \quad (5.1)$$

non linear in x and u . The outputs can be subdivided in those controllable only with the inputs and those that are also function of the states,

$$y_1 = h_1(x) \quad (5.2)$$

$$y_2 = h_2(x, u) \quad (5.3)$$

The states, as above mentioned, are the mass and temperature in the lower pile, temperature in upper pile and gas flame and flue gasses outlet temperature. The time derivative of the waste is a vector $\dot{M}_L \in \mathbb{R}^4$, whose elements are the changes in water, volatiles, fixed char and inerts. The changes due to thermodynamical processes can then be written as

$$d_{thermal} = \begin{bmatrix} f(M_{LL}, T_L, f_p, T_p) e'_1 (e_1(M_{LL}/\mathbf{1}M_{LL}) \\ f(f_p, T_p) e^{-E_a/RT_{LL}} e'_2 M_{LL} \\ e^{-E_a/RT_{LL}} e'_3 M_{LL} \\ 0 \end{bmatrix} \quad (5.4)$$

The overall mass changes are therefore:

$$d_{1,waste} = d_{thermal} + V_g k_v M_{LL} \quad (5.5)$$

$$d_{1,gas} = \begin{bmatrix} 0 \\ d_{thermal}(2) \\ d_{thermal}(3) \\ d_{thermal}(4) \end{bmatrix} \quad (5.6)$$

The ash bunker, where the ashes falling from the last pile, n , are collected, can be seen as an infinite sink modelled by the equation

$$\dot{x}_{AB} = -V_g^n k_v M_{LL}^n \quad (5.7)$$

Global waste mass balance (including the ash bunker), yields

$$\dot{m} = \left[\sum (V_g^{i-1} k_v M_L^{i-1}) - (V_g^i k_v M_L^i) - d_{1,waste}^i \right] + (V_g^n k_v M_L^n) = f_w^0 - \sum d_{1,waste}^i \quad (5.8)$$

with $f_w^0 \in \mathbb{R}^4$ is the incoming waste from the feeding system.

In the upper layer the only state is the temperature, T_u and its change $\dot{T}_u$ is a function of the conductive heat transfer and radiative transfer with the flame. The conductive heat transfer is a stabilizing element, since it tends to equalize the temperatures in the upper and lower layer, as described in Chapter 4. The gas cloud has also only one state, the gas temperature T_f , and it changes thanks to radiative heat transfer with the burning bed, and the primary and secondary combustion processes and the incoming energy from the secondary air.

As described in details in Chapter 4, each of the thermochemical processes is bound to a heat release or absorption. This heat flow is proportional to the mass change, with constants k (a physical explanations of these constants can be found in Chapter 4;

$c_p \in \mathbb{R}^4$: heat capacity for the different materials (waste, air, combustion gasses), as given by the equations

$d_2 = k d_1 \in \mathbb{R}^4$: evaporation, combustion, pyrolysis heat

$d_3 = k_r [T_{GC}^4 - T_u^4] \in \mathbb{R}$: radiative heat exchange

$d_4 = k_c [T_u - T_L] \in \mathbb{R}$: conductive heat exchange

$d_5 = f(f_s, T_s, Q) e^{-k/RT_{GC}} e'_3 f_{GC} \in \mathbb{R}$: heat of gas combustion

$d_6 = k_{wg} (T_L - T_g(f_p, T_p)) \in \mathbb{R}$: heat exchange between gas and waste

The states in the lower layer are the mass (in its four components) and the temperature, hence:

$$\begin{bmatrix} \dot{M}_{LL} & \dot{T}_{LL} \end{bmatrix} = G_{LL} \begin{bmatrix} f_w \\ T_w \\ Vg \end{bmatrix} + k_{LL} \begin{bmatrix} d_{1,waste} \\ d_2 \end{bmatrix} + d_4/c_{pw} M_{LL} e'_5 + (c_{pw} f_w T_w / c_{pw} M_{LL}) e'_5 + d_6/c_{pw} M_{LL} e'_5, \quad (5.9)$$

where

$$G_{LL} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & -e_1 \cdot k_v \cdot M_{LL} \\ 0 & 1 & 0 & 0 & 0 & -e_2 \cdot k_v \cdot M_{LL} \\ 0 & 0 & 1 & 0 & 0 & -e_3 \cdot k_v \cdot M_{LL} \\ 0 & 0 & 0 & 1 & 0 & -e_4 \cdot k_v \cdot M_{LL} \\ 0 & 0 & 0 & 0 & 0 & -k_v c_{pw} M_{LL} T_L \end{bmatrix}$$

$$K_{LL} = \begin{bmatrix} -I^{4 \times 4} & -0^{4 \times 4} \\ -0^{1 \times 4} & -[1 \ 1 \ -1 \ 1]/c_p \cdot M_{LL} \end{bmatrix}$$

The only state in the upper layer is the waste temperature, T_u satisfying the equation:

$$\dot{T}_u = 1/c_{pw} M [1 \ -1] \begin{bmatrix} d_3(T_{GC}, T_u) \\ d_4(T_{LL}, T_u) \end{bmatrix} \quad (5.10)$$

The waste temperature tends to equalize the temperatures in the upper and lower layer, via the conductive heat transfer, as from Chapter 4, section Drying. The only state in the gas cloud is the gas temperature satisfying

$$\dot{T}_{fg} = c_{pg} f_g T_g - c_{pf} f_f T_{GC} + [-1 \ 1] \begin{bmatrix} d_3(T_{GC}, T_u) \\ d_5(f_s, T_s, Q, T_{GC}) \end{bmatrix} + c_{ps} f_s T_s + Q \quad (5.11)$$

The gas mass f_{GC} is calculated statically, as the sum of the combustion products from the single piles, the secondary air and the secondary combustion products, G_{mg} .

$$f_{GC} = \sum (f_p^i + d_{1,thermal}^i) + f_s + G_{mg}(T_{fg}) \quad (5.12)$$

where i is the pile number.

The state in the boiler is the outlet temperature of the flue gasses:

$$\dot{T}_{GO} = \frac{[(f_f (T_f - T_{GO}) - \kappa (T_{GO} - T_{so}) / (c_{pf} \cdot f_f)]}{M_f} \quad (5.13)$$

being T_{so} the temperature of the outgoing steam and κ is the conduction transfer coefficient. The model has been implemented in Matlab/Simulink. As part of the model implementation, local stability of the model is proven by linearization in the neighborhood of an equilibrium point x_0 . Moreover the linearized system is observable and controllable. From the analysis

of the input-output zeros and step response the linearized model is shown to be nonminimum phase for some input/output couples.

Chapter 6

Real Time Parameter Estimation

6.1 Background of the invention

This chapter describes an invention made during the studies for the final dissertation. The final control solution described in Chapter 7 does not apply the invention here described. As already explained in details in Chapter 2, one of the main problems encountered in controlling the waste incineration process is the extreme variability of the fuel composition and the lack of information about it. In many industrial application the different control variables are controlled independently one from the other, with single loops and PID controllers. Sometimes even open loops are still used.

The invention is based on the thermal balance of the process, assuming that the waste temperature can be measured. Strictly from the energy balance point of view, assuming complete combustion of the fuel, no losses and unitary boiler efficiency, the total energy contained in the steam is equal to the sum of the energy in the waste and that of the combustion air. Introducing the concept of enthalpy, the energy balance over the combustion zone can be written as:

$$S \cdot H_{steam}(T_{steam}, P_{steam}) = [f_w \eta LHV + f_p H(T_p) + f_s H(T_s)] \quad (6.1)$$

Being

$0 \leq \eta \leq 1$ = fuel conversion efficiency

f_w = Waste feed rate

f_p, T_p = Primary air mass flow, Primary air temperature

f_s, T_s = Secondary air mass flow, Secondary air temperature

H = Enthalpy

S = Steam flow rate

where the parameter ηLHV is undetermined. The waste flow f_w is one of the main control input, together with the primary and secondary air. The equality 6.1 always provides a solution, which means, a value of $f_w \eta LHV$ such as the steam flow rate S is achieved. For values of η other than one and without knowing the lower heating value, it is not possible to draw any correct conclusion on the waste flow required to fulfill the equality. On the other side, the steam production S can also be expressed in terms of an energy balance over the boiler, using the same nomenclature as in Chapter 5.

$$S \cdot H_{steam}(T_{steam}, P_{steam}) = \tilde{\eta} \dot{m}_{gas} [f_p, T_p, f_s, T_s, d_{1,gas}(T_{LL}, f_p), G(T_f, f_s)] H_{gas}(T_f) \quad (6.2)$$

with $\tilde{\eta}$ = Boiler efficiency

T_f = Flame temperature

T_{LL} = waste temperature

This equation is strongly nonlinear and the dependency from the incoming waste flow is not clearly identifiable, therefore it is not possible to use it straightforwardly to calculate a control value of f_w to reach a desired amount of steam S .

The goal of this invention is to find a regression expressing the steam flow rate S as a function of some inputs and states of the system (amongst them, the waste bed temperature). Such a function is then used to exactly calculate the waste feed rate f_w required to obtain a desired steam flow rate S , replacing for instance a PID controller previously implemented. We try to combine equation 6.1 and 6.2 in an equation that while still being nonlinear in the inputs, is linear in some parameters θ . The aim is to estimate these parameters θ using the Recursive Least Square method. Once such parameters are found, a chosen polynomial is used to exactly calculate the waste mass flow rate. The mass flow rate is then used in a closed loop configuration in order to produce a desired amount of steam.

6.2 Detailed description of the invention

The chosen polynomial has the form:

$$y(t) = (\theta(1)\phi_1 + \theta(2)\phi_2 + \theta(3)) \cdot c_p \cdot T_f + \theta_4 \quad (6.3)$$

being

$$\phi_1 = (f_p + f_s)^n \text{ where } n \approx 1.8$$

$$\phi_2 = f_w A_1 e^{-\frac{E_1}{RT_{LL}}} A_2 e^{-\frac{E_2}{RT_f}}$$

$\hat{y}(t)$ = steam flow [kg/s]

c_p =flue gas specific heat [kJ/Kg, K]

A_1, A_2, R, E_1, E_2 are constants known from literature [23], [26].

The first term ϕ_1 represents the contribution of primary and secondary air. The second term, ϕ_2 , represents the combustion gasses originated from the solid and gaseous combustion. The term $A_1 e^{-\frac{E_1}{RT_{LL}}}$ gives the combustion rate of the solid phase as a function of the waste temperature, while $A_2 e^{-\frac{E_2}{RT_{GC}}}$ gives the combustion rate of the gaseous phase as a function of the flame temperature. The waste temperature considered is the one in the main combustion zone. This value can be determined using any of the existing methodologies, such as an infrared camera. Once the vector of parameters θ has been identified, it can be used to directly calculate the amount of waste needed to obtain a desired steam flow set point. We have in fact a relation of the form:

$$y(t) = M(\theta) + f_w N(\theta) \quad (6.4)$$

From which it follows

$$f_w = (y^* - M(\theta)) / N(\theta) \quad (6.5)$$

Being $y^*(t)$ the steam set point. As there is a delay between the feeding of the waste onto the grate and its effect on the steam production, a corresponding delay time Δ is introduced into the relations above. This time delay can be in the order of up to one hour, and physically relates to the waste residence time in the initial grate zone. By using the mass flow from equation 6.5 we are trying to correct instantaneously something that is actually an effect of the input at time $(t - \Delta)$. The aforementioned linear relation then read:

$$y^*(t) = M(\theta) + f_w(t - \Delta)N(\theta) \quad (6.6)$$

The time delay Δ is not known and it can physically be seen as the waste residence time in the initial grate zone.

6.3 Results and conclusions

According to the invention, the steam production in a waste combustion process is controlled by determining waste feed rate control values from a relation approximating the steam flow as a sum of independent steam contributions depending on operational parameters that are accessible in real-time. The operational parameters include process inputs such as mass flows

of primary and secondary combustion air, as well as process states such as waste and flame temperatures. The independent steam contributions are inspired by the real physical part-processes and account for the strong non-linearity of the combustion process in the operational parameters. These contributions are multiplied by process-specific, a-priori unknown regression coefficients accounting for all kinds of uncertainties or variations in the combustion process. Hence, the proposed polynomial approximation of the steam flow separates the contributions depending in a non-linear way on the measured process inputs and states from a limited number of linear regression coefficients that are nevertheless capable of capturing all possible variations of the waste composition if properly chosen. The process-specific values of a number N' of the coefficients θ are derived or tuned in a training step from N data sets comprising operational values, i.e. values measured during operation of the specific incineration plant, of the operational parameters and corresponding steam flows, using a recursive least square. In an advantageous embodiment of the invention, the operational values of the data sets that are evaluated in order to derive a relation or expression relating the steam flow to the operational parameters comprise values of a waste temperature or a combustion temperature. From this relation, an optimal waste feed rate to obtain a desired steam output is determined and applied to the waste feed actuator of the waste incineration plant.

The invention has been tested on the model described in Chapter 5, with constant waste composition $\alpha=[0.10, 0.50, 0.35, 0.05]$ and a steam flow rate target varying from 36 t/h to 28 t/h. The results are displayed in Figure 6.1 and in Figure 6.2. The oxygen is kept at its target level of 8% with a PID controller. It can be seen in Figure 6.3 how the coefficients θ vary with a varying steam flow rate target.

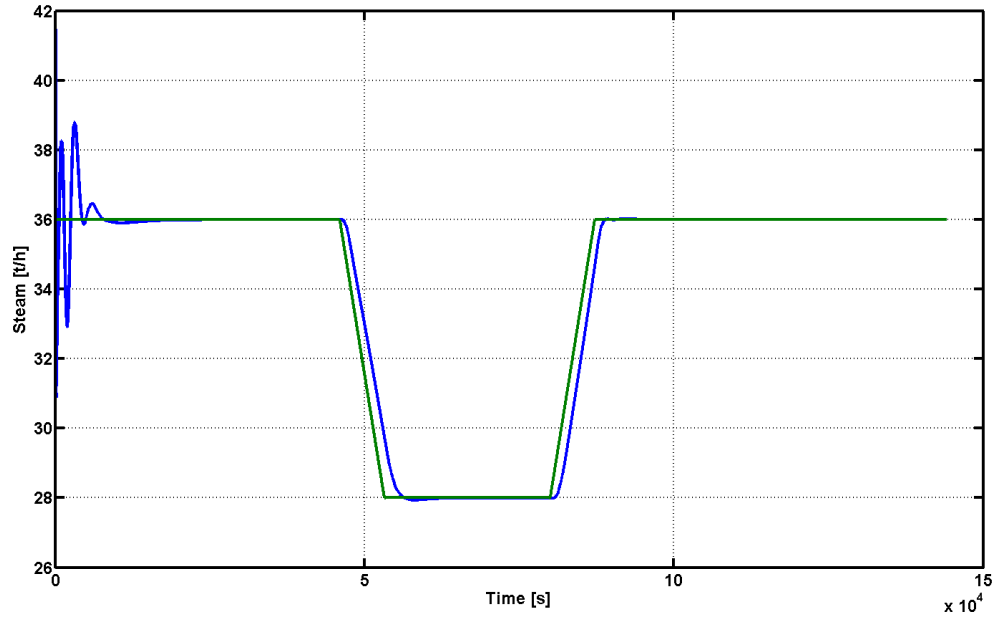


Figure 6.1: Steam flow [t/h] (blue) against steam flow setpoint [t/h] (green). The waste incineration process is modeled using the model described in Chapter 5. The waste composition is assumed constant $\alpha=[0.10, 0.50, 0.35, 0.05]$.

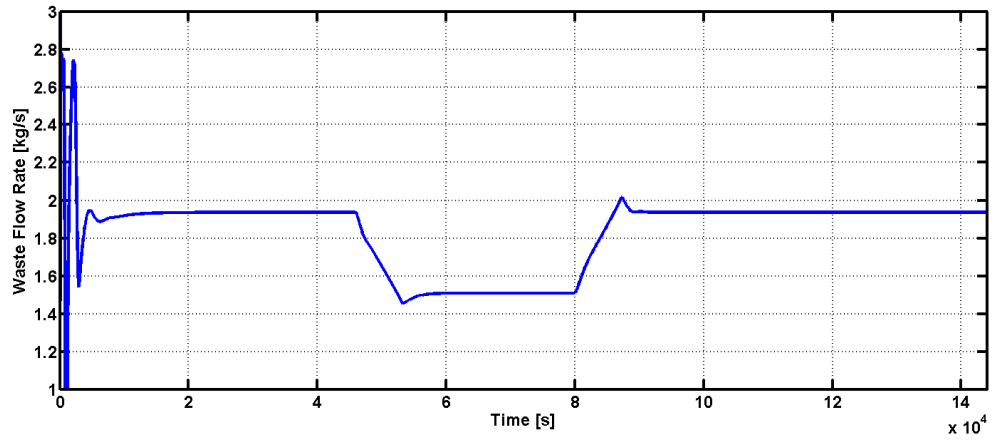


Figure 6.2: Waste flow $[kg/s]$. The waste incineration process is modeled using the model described in Chapter 5. The waste composition is assumed constant.

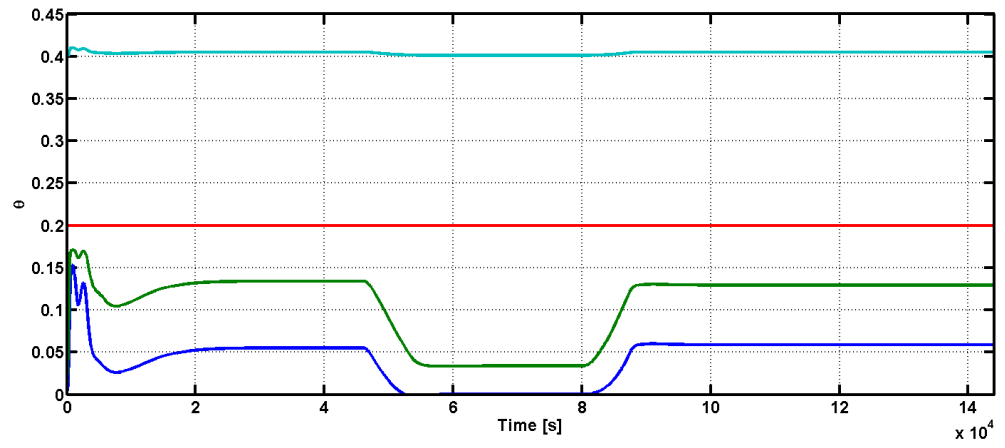


Figure 6.3: Regression coefficients θ . The waste incineration process is modeled using the model described in Chapter 5. The waste composition is assumed constant.

This invention offers a simple but valid methodology to determine the optimal waste flow to keep a desired steam set point, given inputs and states easily measurable in a plant.

Chapter 7

Input/Output Linearization

In the previous chapters we have described the incineration process, in Chapter 3 and how it has been modelled, Chapter 5. Chapter 1 reviews standard industrial control solutions, while Chapter 6 describes a new control approach based in Least Square Regression. The approach presented in this chapter differs from those described previously and bases itself on the concept of input/output linearization. Firstly, in Section 7.1 we review the concept of Zero Dynamics for a single-input single-output system. Secondly, in Section 7.2 we show how this concept can be used to control the waste incineration process by implementing an appropriate solution and testing it on the model described in Chapter 5.

7.1 Zero Dynamics

The idea behind input/output linearization is to see if there exist a state feedback control and, if needed, a change of variables, that transform a nonlinear system into an equivalent linear system [35]. In order for this to be possible, the nonlinear system must have a certain structure. Specifically, to cancel the nonlinearities, the control u and the nonlinearities must appear always together as a sum or as a product. That means that the multiple variable nonlinear system must have the form

$$\dot{x} = f(x) + \sum g(x) u \quad (7.1)$$

$$y = h(x) \quad (7.2)$$

in which $f(x), g(x)$ are smooth vector fields and h a smooth function defined on an open set of $\mathbb{R}^n$. The starting point of this analysis is the concept of relative degree. The relative degree r can be seen as the number of times one has to differentiate the output $y(t)$ at time $t = t^o$ in

order to have at least one component of the input vector $u(t^o)$ explicitly appearing. Imposing the derivative of order r of $y(t)$ to be zero,

$$y^r(t^0) = L_f^r h(x^0) + L_g L_f^{r-1} h(x^0) u(t^0) = 0 \quad (7.3)$$

the zeroing input $u^*(t)$ can be calculated as

$$u^*(t^0) = \frac{-L_f^r h(x)}{L_g L_f^{r-1} h(x)} \quad (7.4)$$

using the notion of Lie derivative or derivative of h with respect to f , that means the derivative of h along the trajectories of the system $\dot{x} = h(x)$.

$$L_f h(x) = \frac{\partial h}{\partial x} \quad (7.5)$$

$$L_f^r h(x) = \frac{\partial L_f^{r-1} h}{\partial x} f(x) \quad (7.6)$$

The idea is always of solving the problem of zeroing the output (or tracking a reference output), i.e. to find initial conditions and inputs consistent with the constraint that the output function $y(t)$ is identically zero (or equal to the reference $y^*(t)$) for all times in a neighbourhood of $t = 0$, and then to analyze the corresponding dynamics [36]. These dynamics correspond to the dynamics describing the internal behaviour of the system when input and initial conditions have been chosen in such a way as to constrain the output to remain identically zero and are called the zero dynamics. It is possible to draw a parallel between the linear case and the non linear one concerning minimum phase. The nonlinear system above described is said to be locally asymptotically (exponentially) minimum-phase at x_0 if the equilibrium point $\eta(0)$ of the zero dynamics is locally asymptotically (exponentially) stable [37].

7.2 Non Linear Control

Opposite to many common control approaches (as described in Chapter 1), in this study the problem is treated globally, without decoupling the dynamics. It is assumed to have a flame temperature measurement, such as an infrared camera, or a camera in the visible, providing online measurements of the waste bed temperature. Maintaining a stable combustion zone ensures a correct temperature profile on the grates, an optimal heat release and correct flue gas residence time. Moreover a correct temperature profile makes sure that the waste is completely burnt before falling into the ash pit, reducing therefore the heat losses and improving the

ash quality. A correct combustion profile can be obtained by a combination of the usual control variables, waste feed rate, grate speed, primary and secondary air. Given a waste bed temperature target profile and a constant waste composition, at steady state the steam flow rate will converge to a constant value. Should the waste composition vary, a different set of inputs is needed in order to maintain the same steam flow rate, or, if some constraints on the inputs are reached, it might not be possible to keep it at all. The first step is to reach a given temperature profile, even under varying waste composition. At the same time additional outputs, such as the residual oxygen in the flue gas or the combustion chamber temperature should be kept within specified values and the inputs must fulfill their constraints. In a second step, described in Chapter 8 we define a new set of values for the waste bed temperature, i.e. a temperature profile, such as to maximize the steam flow rate. The presented solution relies on the concepts of input/output linearization [36], [38] and extremum seeking [39]. The extremum seeking is treated in Chapter 8. Stability is achieved using the approach described in [36]. Each pile is described according to the equations in Chapter 5 and for each one we impose its temperature equal to a reference value. We moreover ask that the oxygen $O_2, [-]$ and waste bed height $h_w[cm]$ for the second pile reach certain reference values. The waste bed height is calculated as a function of the waste density $\rho_{waste}, [kg/m^3]$, waste composition α in fraction, waste mass $x_{LL}, [tons]$ and grate zone area $A, [m^2]$.

The system is

$$\dot{x} = f(x) + \sum g(x) u \quad (7.7)$$

$$y_1 = h_1(x) \quad (7.8)$$

$$y_2 = h_2(u, x) \quad (7.9)$$

$$\dot{y} = \frac{\partial h}{\partial x} [f(x) + g(x)u] = L_f h + L_g h u \quad (7.10)$$

The input-output linearization approach is used to control the outputs y_1 . The vector relative degree [36] for this system is $r = [1 \ 1 \ 1 \ 1]$, meaning that the first time derivatives of the output are explicit function of the input. As a result, there exists an input u such that, for any output constant reference value y^* , the equation

$$\dot{y} = f(x, u) + g(x)u = -k(y - y^*) \quad (7.11)$$

with $k > 0$, has a solution. The proportional term takes into account deviations from the initial conditions. The solution is subject to constraints due to the actuator limitations. The constraints define for instance the total air flow range, the maximum waste flow rate or maximum

grate speed and they are expressed in the form $Au \leq B$. Therefore the control input vector computed as the solution of the minimization problem

$$\min \|f(x, u) + g(\cdot)u + k(y - y^*)\|^2. \quad (7.12)$$

In our study we limit ourselves to tracking reference values for the bed temperatures in the second and third pile as the combustion happens mainly here. This is done by multiplying the error terms relative to the remaining outputs by some small weights, in the order of 10^{-1} to 10^{-3} . In this case the reference values for those outputs are only tracked if the deviation is big.

7.2.1 Simulation at steady State

The first test consists of fixing the reference values for the waste bed temperature and checking if the implemented algorithm succeeds in achieving these steady states conditions. To reduce the calculation load, the function is solved only every $t, [s]$. The waste composition $\alpha \in \mathbb{R}^4$ is assumed to be constant; the elements of the vector are respectively water, char, volatiles and inerts. In a first test the waste composition has been kept constant and we ask the temperature for the second and third pile reach some target values. If the reference varies, the step response

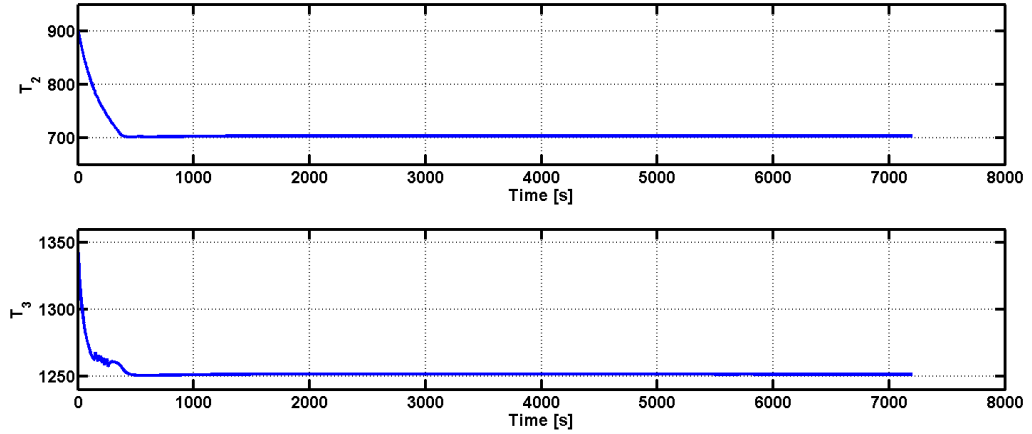


Figure 7.1: Input/Output Linearization: The reference temperatures are $T_2 = 700\text{ K}$ and $T_3 = 1250\text{ K}$. The waste composition is assumed as $\alpha = [0.2, 0.3, 0.3, 0.2]$. The initial conditions for the temperature in the second and third pile were $T_{0_2} = 800\text{ K}$ and $T_{0_3} = 1350\text{ K}$.

is very fast, see Figure 7.4. We can see that it takes approximately three minutes to reach the new target, for both piles. The change in waste temperature is achieved by varying the primary and secondary air flow, see Figure 7.5.

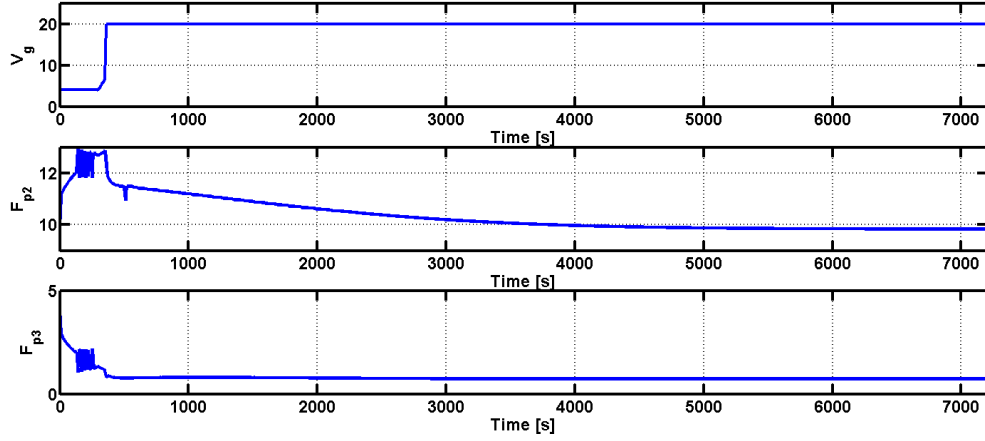


Figure 7.2: Input/Output Linearization: The change in waste temperature is achieved by varying the primary and secondary air flow.

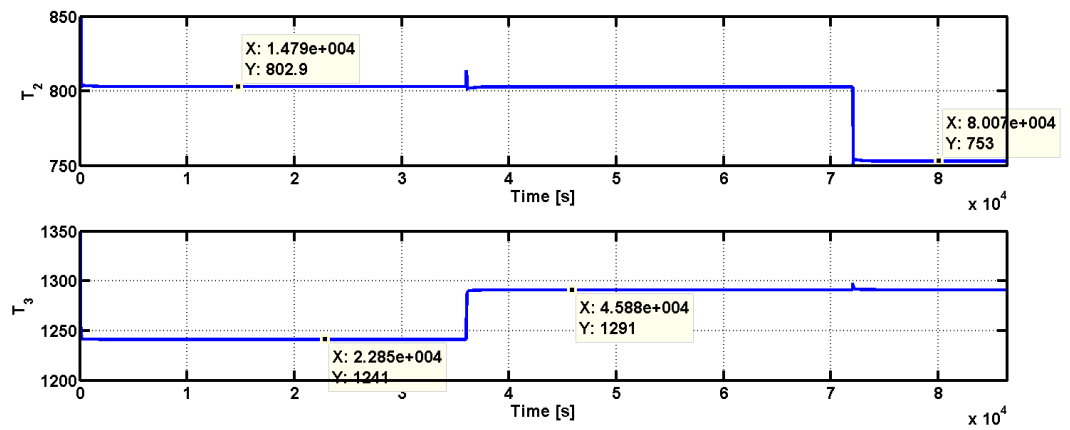


Figure 7.3: Step Response: Step response to a change in temperature reference for the second and third pile. The system reacts quickly to a set point change, either when only one pile set-point is changed or when both are. The waste composition is assumed as $\alpha = [0.2, 0.3, 0.3, 0.2]$.

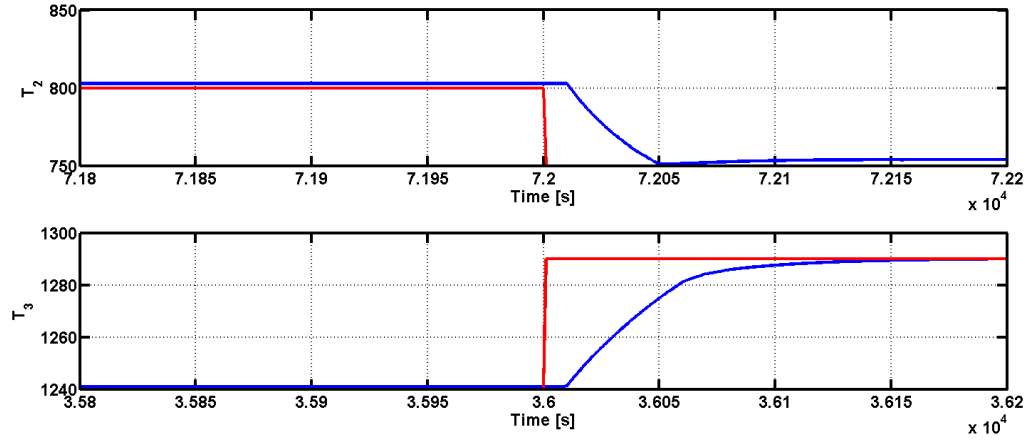


Figure 7.4: Step Response Details: Step response to a change in temperature reference for the second and third pile. The system reacts very quickly to a set point change (red). The time constant is about 3 minutes for a step change of 50 K.

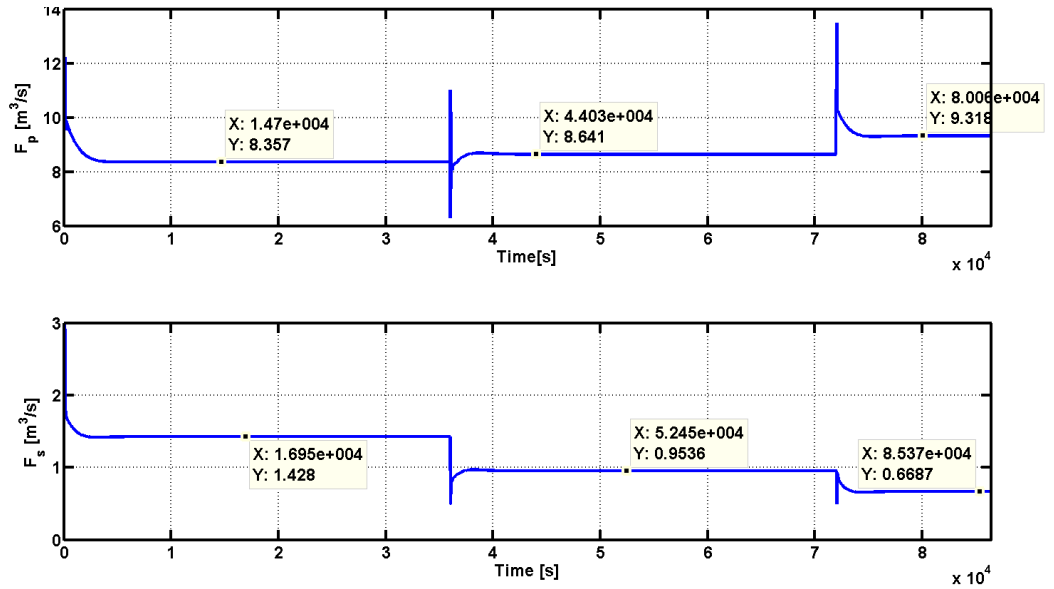


Figure 7.5: Step Response Controls: Step response to a change in temperature reference for the second and third pile. The temperature is controlled by changing the primary air flow rate under the second and third pile.

7.2.2 Variable Waste Composition

As already mentioned in Chapter 2, the waste composition is highly variable and cannot be measured on line, therefore any control strategy must be robust against its variation. The waste composition α varies dynamically during the simulation. The water and combustible material fractions (fixed carbon and volatiles) are normally distributed random numbers, with a given mean and variance, while the ash fraction is obtained by normalization. In a real scenario it would be reasonable to assume a waste composition change every 20-30 minutes. This is compatible with the waste amount grabbed by the fresh feed crane, that is in the order of 2 – 3 tons , for a middle sized plant. Considering a deep enough waste bunker and a competent crane operator, it is reasonable to expect that the changes over this period is relatively modest, while the composition can vary even significantly on daily, weekly and seasonal base. By making a step change in the waste composition we can determine the time constant of the process. This time turns out to be about half hour.

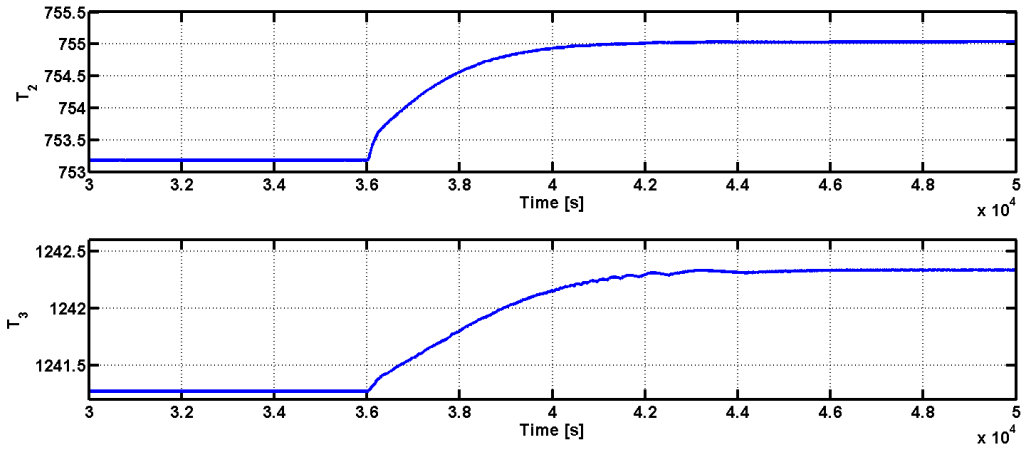


Figure 7.6: Waste Bed Temperature for varying waste composition. The reference values are $T_2 = 750\text{ K}$, $T_3 = 1240\text{ K}$; we can see how the third pile is virtually unaffected by a change in waste composition. The initial waste composition is $\alpha_1 = [0.2, 0.3, 0.3, 0.2]$ for a lower heating value $LHV = 14\text{ kJ/kg}$, the new waste composition is $\alpha_2 = [0.15, 0.3, 0.3, 0.25]$ with a lower heating value $LHV = 14.8\text{ kJ/kg}$. The control law is successful in converging to steady state even after a change in waste composition.

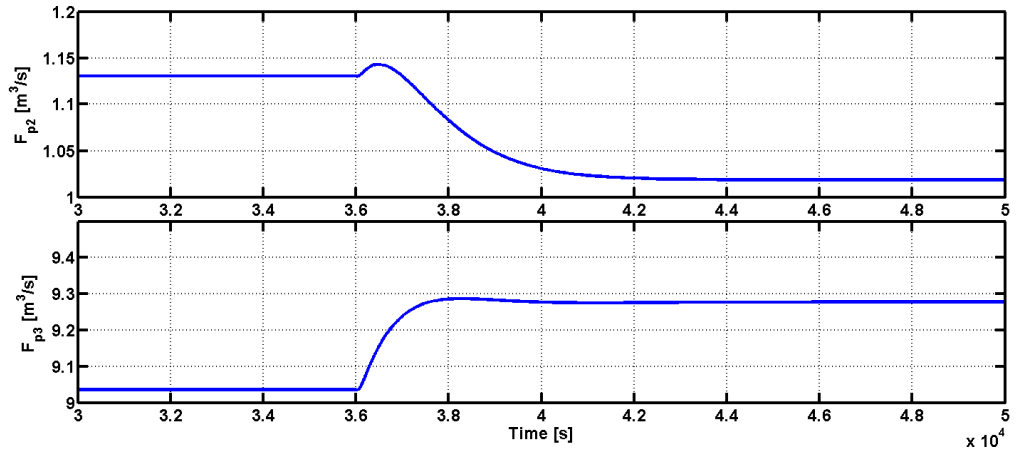


Figure 7.7: Control inputs with variable waste. The new reference values for the temperature in the second and third pile are reached by varying the primary air flow rate.

Chapter 8

Steam Maximization by using Extremum Seeking

We have described in Chapter 7 how we can stabilize the system described in Chapter 5 around some sets of waste bed temperature. We now want to regulate the output close to this extremum without any prior knowledge of the waste composition. The choice is to use the extremum seeking approach, [39], [40], [41]. The extremum seeking in its nature is a gradient search method which can extract the gradient of the unknown reference-to-output mapping [42]. Extremum seeking does not require a precise knowledge of the equilibrium map, only the existence of maximum and that the general nonlinear system can be stabilised around each of these equilibria by a local feedback controller. The solution used in this study is based on the results from [40]. Specifically to our problem, the static map $g(\cdot)$ is the combustion and steam generation process, the disturbance d is the unknown waste composition, and the probing signal θ is the waste temperature.

In Section 8.1 we show that the steam flow presents at least a maximum for some temperature couples T_2 , T_3 and constant oxygen target, while in Section 8.2 we describe how the Extremum Seeking theory has been applied to the system and we show some results.

8.1 Sensitivity analysis on pile temperature

In Chapter 7 we have shown how it is possible to reach certain couples of temperatures T_2 , T_3 for the second and third pile by means of input-output linearization. The question arises which are the temperature couples that maximize the steam production. We need to prove that for varying temperature setpoint values and constant waste composition, the steam production shows a maximum. The analysis of the results has to limit itself to the temperature range

where the limits on waste temperature, bed height and oxygen are respected; steam values for which the limits are not respected should be discarded. In other words, should it not be possible to find a solution for the minimization problem described in Equation 7.12 within a certain tolerance, the results should not be considered in the rest of the study. As the control variables are constrained, as defined previously, some set points cannot be reached (even if they could be reached with a different set of constraints). We nonetheless leave the constraints unvaried because we want to test the sensitivity to the waste bed temperature while remaining within a realistic plant configuration.

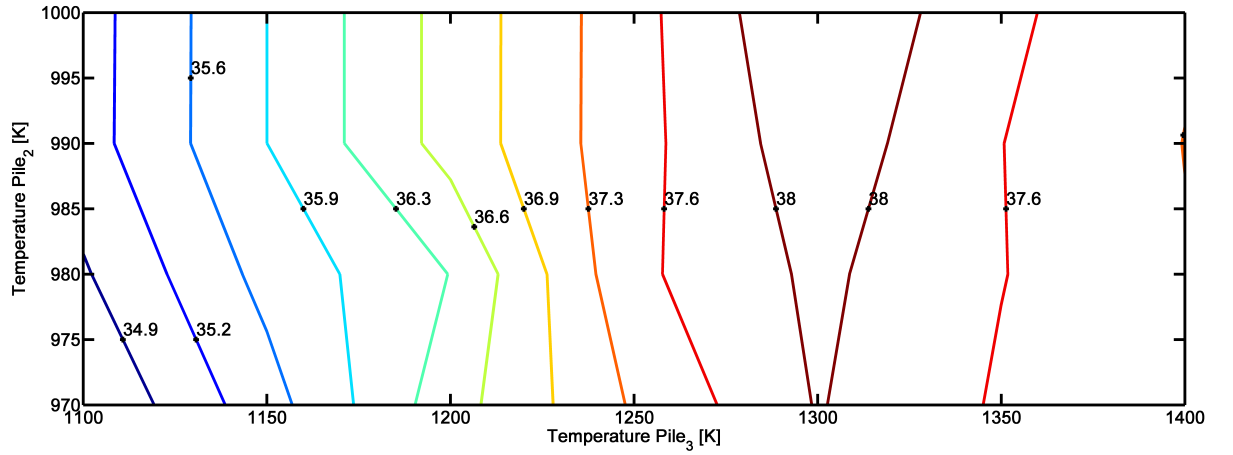


Figure 8.1: Sensitivity analysis of steam flow rate against piles temperature. The steam flow rate (in t/h) has been simulated for different values of the temperatures of the second and third pile, T_2 , T_3 . For each simulation the waste composition is $\alpha = [0.20, 0.30, 0.30, 0.20]$. The steam flow rate value is plotted next to the corresponding curve.

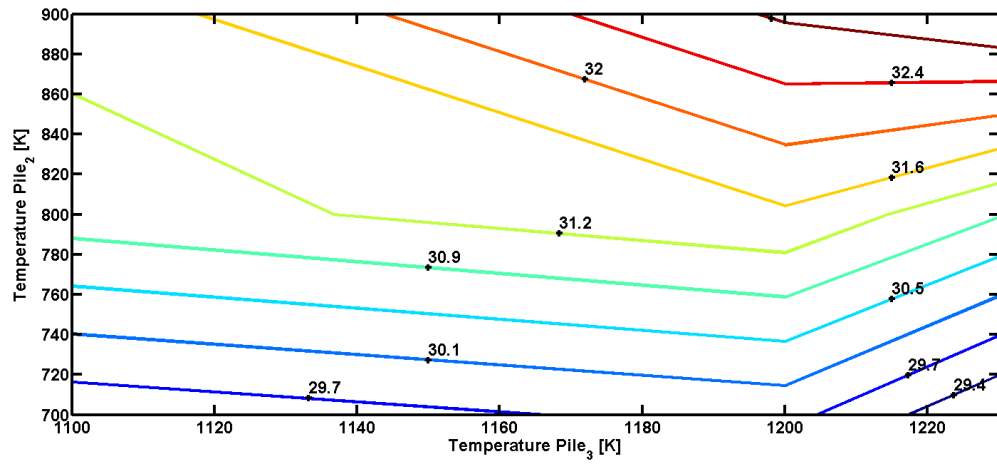


Figure 8.2: Sensitivity analysis of steam flow rate against piles temperature. The steam flow rate (in t/h) has been simulated for different values of the temperatures of the second and third pile T_2 and T_3 . For each simulation the waste composition is equal to $\alpha = [0.25, 0.25, 0.25, 0.25]$. The steam flow rate value is plotted next to the corresponding curve.

As seen from Figure 8.1 and Figure 8.2, assuming a constant waste composition we identify a waste bed temperature range containing a relative maximum for the steam flow rate. It is important to stress that since in the input/output linearization the temperatures in the first and fourth pile, as well as the oxygen and second bed pile height are controlled within a deadband, different initial condition lead to different outputs. In these sensitivity analysis each simulation has as initial conditions the final conditions of the previous simulation, that means, the model is initialized with an initial state $(x_0)_i = (x(t_f)_{(i-1)})$. The input/output linearization routine is as well initialized for every new simulation with the final input vector from the previous simulation. The next step is therefore to find a way of determining the steady state temperature setpoints that maximise the steam production, even when the waste composition varies. At the same time the constraints and the conditions on the remaining states should be respected.

8.2 Extremum Seeking Analysis

The extremum seeking has been implemented as an external loop providing set points for the waste bed temperature in the second and third pile θ ; the input/output linearization stabilizes the system around these values. In this way we achieve maximization of a certain output, for instance the steam flow y , without any knowledge of the waste composition. Given the constraints on the inputs it is not always possible to maximize the steam production directly therefore we have decided to minimize instead a pseudo-quadratic cost function of the steam and given steam minimum and maximum targets, see Equation 8.1. While the solution described in [40] uses derivatives, we use a time delay to avoid reacting to the short term process noise as shown in Figure 8.2. Moreover, as the steam maximum is flat, especially along T_2 , the extremum seeking does not maximize the steam directly but instead a cost L calculated as the deviation between the steam error ϵ and the steam flow rate minimal and maximal values m and M .

$$L = \begin{cases} -\epsilon + m, & \epsilon < m \\ -\frac{q\epsilon}{m-M} + \frac{qm}{m-M}, & m \leq \epsilon \leq M \\ \epsilon - M - q, & \epsilon > M \end{cases} \quad (8.1)$$

The constant m , M , and q are positive scalars.

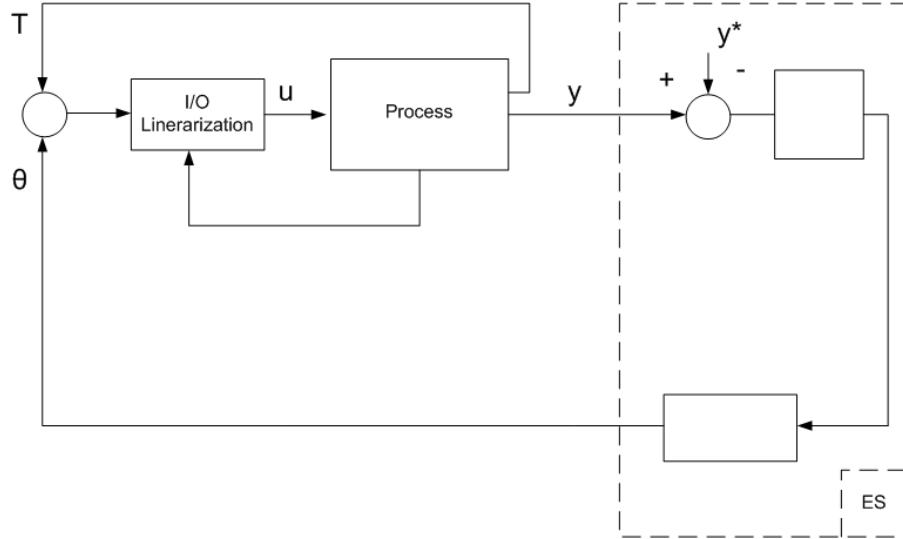


Figure 8.3: Scheme of control solution. The constrained input/output linearization calculates an input vector such that the temperature targets, θ , provided by the extremum seeking routine are reached. The extremum seeking is described in details in Figure 8.2.

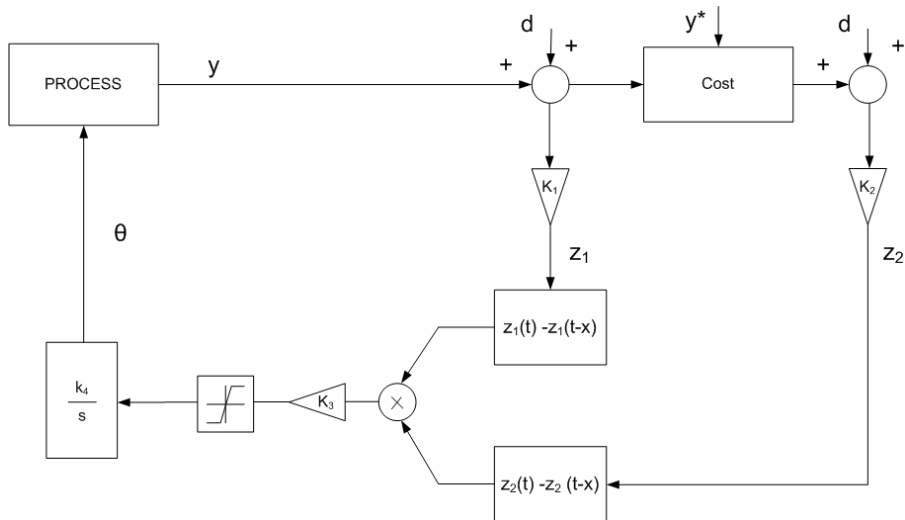


Figure 8.4: Scheme of the extremum seeking solution. The process output is the steam flow rate y , the target steam flow rate is y^* and d a disturbance. The extremum seeking routine minimizes a pseudo-quadratic cost function providing a target value θ for the temperature in the second and third waste bed piles, see Equation 8.1.

Extremum Seeking with constant waste composition

The results of the first test, run with constant waste, are shown in Figure 8.5.

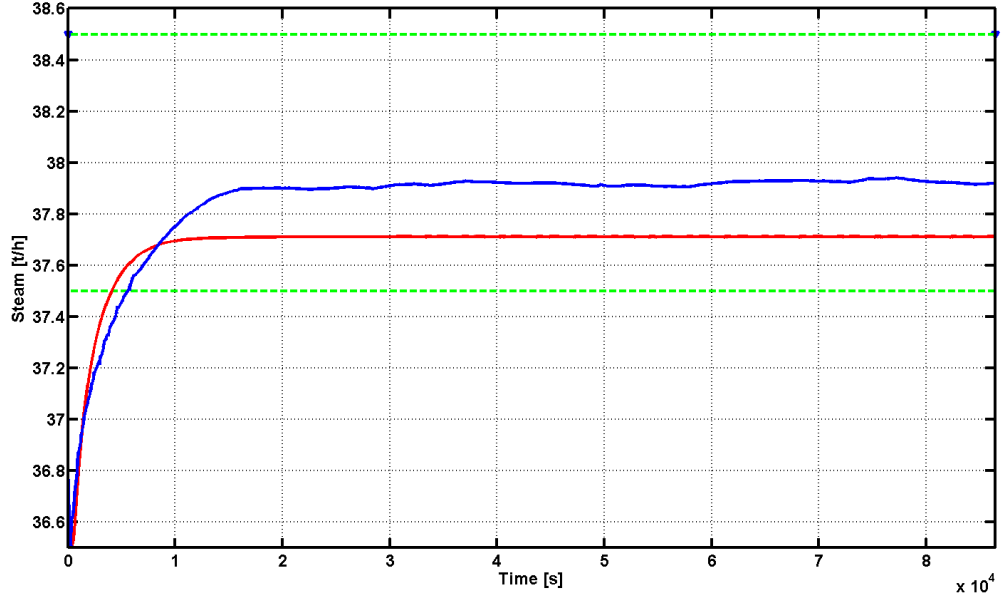


Figure 8.5: Steam Maximization with constant waste composition: Case 1. This figure shows the steam flow rate obtained in the two cases: Red: Fixing $T_2 = 900\text{ K}$, $T_3 = 1350\text{ K}$; Blue: Leaving T_2 and T_3 free to vary. The final new values are $T_2 = 991\text{ K}$ and $T_3 = 1357\text{ K}$. The target steam production is bound to lie in the interval $[37.5, 38.5]$, since, according to Figure 8.1, we expect to find a maximal value for the steam flow in this range.

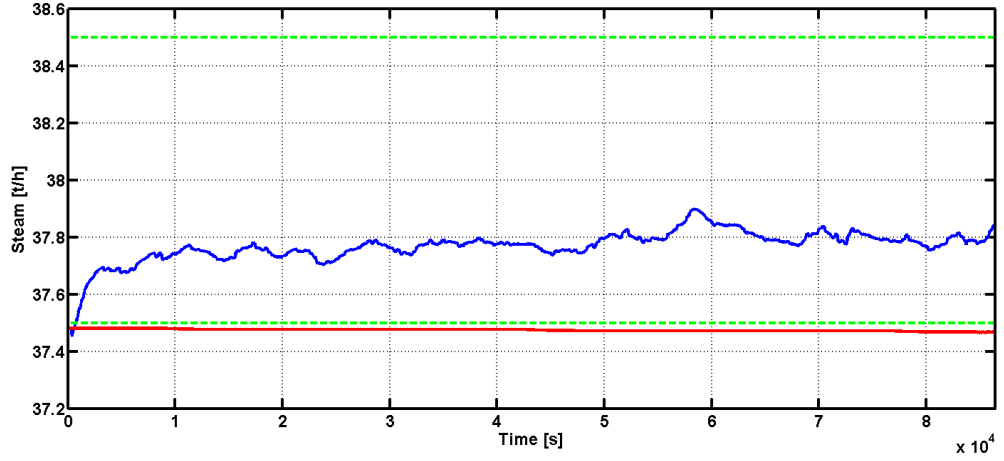


Figure 8.6: Steam Maximization with constant waste composition: Case 2. This figure shows the steam flow rate obtained in the two cases: Red: Fixing $T_2 = 900\text{ K}$ and $T_3 = 1250\text{ K}$ free; Blue: leaving T_2 and T_3 free to vary; The target steam production is bound to lie in the interval $[37.5, 38.5]$, represented by the dashed green lines since, according to Figure 8.1, we expect to find a maximal value for the steam flow in this range.

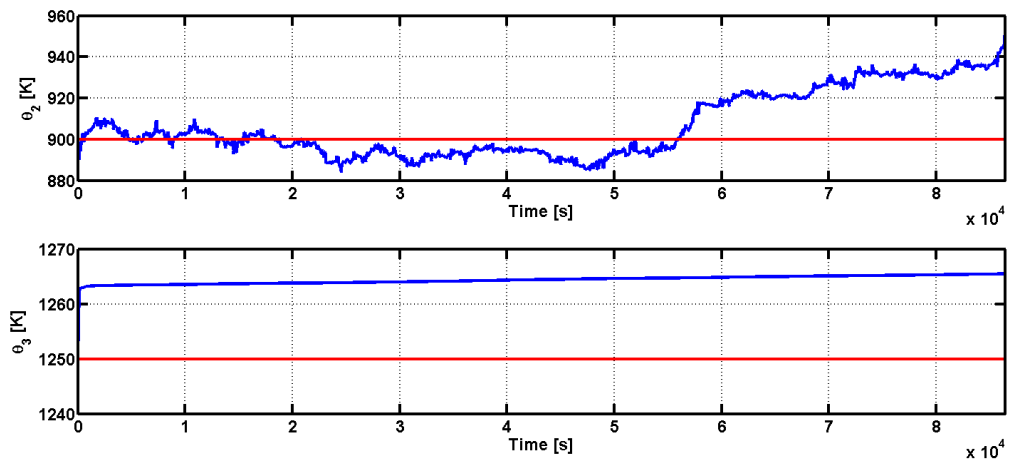


Figure 8.7: Steam Maximization with constant waste composition: Case 2. The temperature reference values vary from their initial values of $T_2 = 900\text{ K}$ and $T_3 = 1250\text{ K}$, plotted in red.

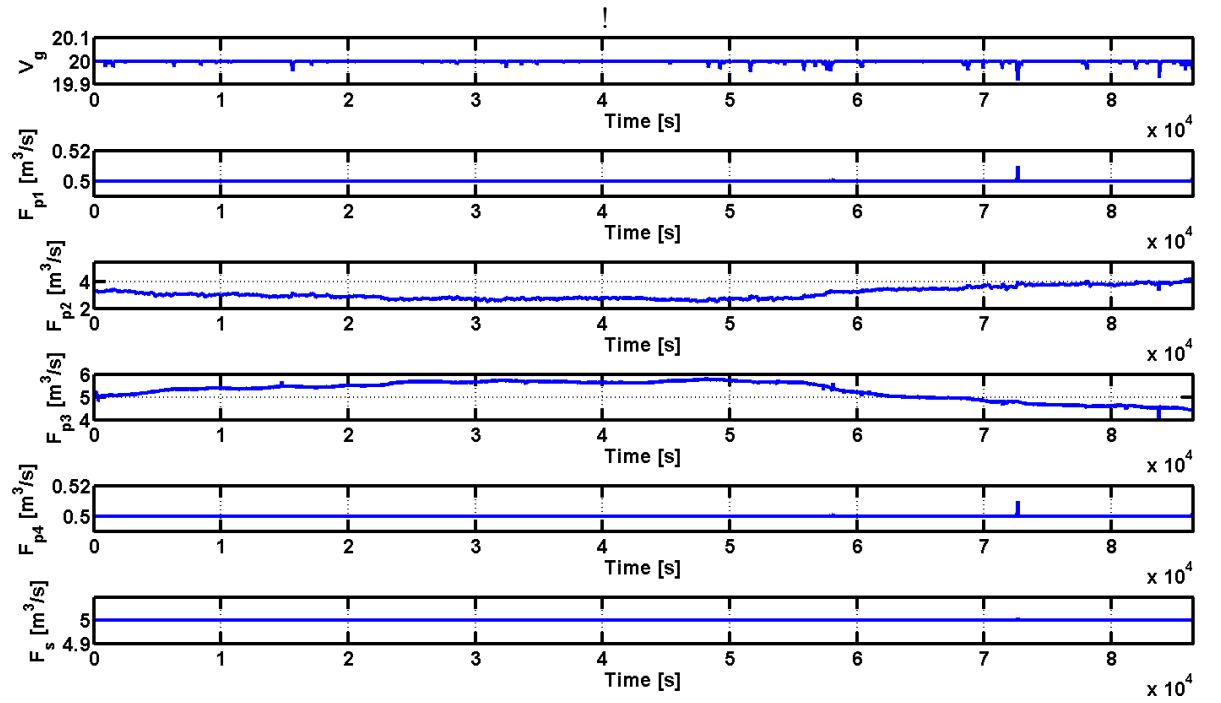


Figure 8.8: Extremum Seeking with constant waste composition: Case 2. The temperature of the waste bed for the second and third pile is kept to a target value by changing the speed grate V_g , the primary air flow rate F_p and the secondary air flow rate F_s .

The results show that the extremum seeking routine calculates new target values for the temperatures of the second and third pile, and this brings indeed to an increase in the steam production. The effect on a change in the temperature set point for the third pile only for Case 1, depicted in Figure 8.5 is not so relevant, due to the fact the temperature set point value is close to the maximum reachable value given the constraints.

Extremum Seeking with variable waste composition

Lastly we test the extremum seeking routine with a variable waste composition. The variable composition is generated randomly, around a nominal composition and it varies with a time constant of 30 minutes. The composition so obtained is filtered over two hours. The waste lower heating value for the variable waste composition and for a constant waste composition α is plotted in Figure 8.9. The lower heating value is calculated using Equation 2.4 and subtracting the latent heat of evaporation. Even in the variable waste case the Extremum

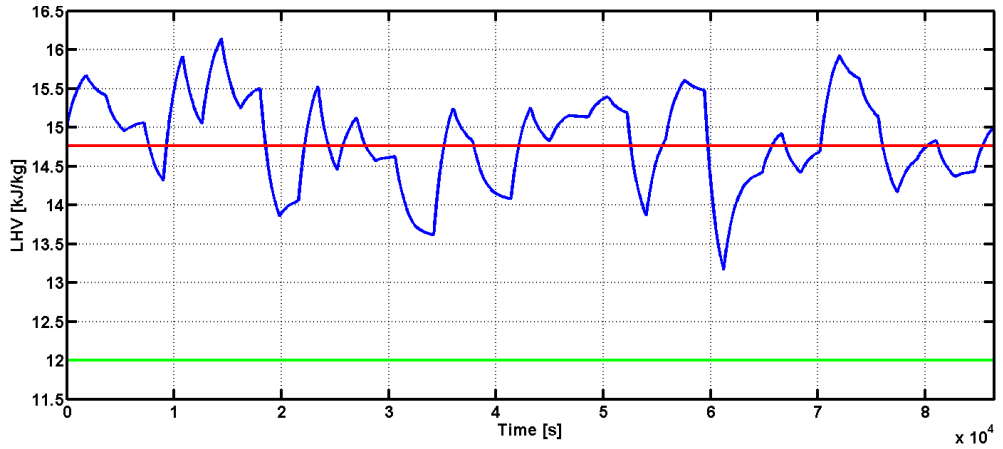


Figure 8.9: Waste Lower Heating Value. The LHV for $\alpha = [0.20, 0.30, 0.30, 0.20]$ is plotted in red, for $\alpha = [0.25, 0.25, 0.25, 0.25]$ is plotted in green while the LHV for a variable waste composition with a time constant of 30 minutes and a filtered over two hours is plotted in blue.

Seeking routine is able to increase the steam production compared to the reference case, Figure 8.10 and Figure 8.13. For Case 1, the starting temperature for the third pile ($T_3 = 1350\text{ K}$) is already close to its limit, and its increase can be counterproductive. For this reason the parameters for the Extremum Seeking in the third pile, listed in Table 8.1, have been chosen such as to have a slow change in θ .

The same test has been repeated with a starting temperature on the third pile of $T_2 = 1250\text{ K}$. The waste bed reference temperature for the second and third piles varies for varying waste

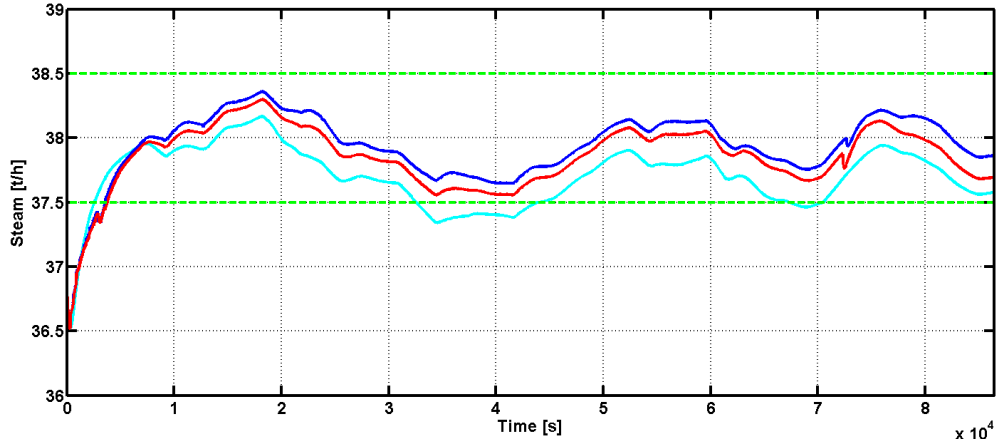


Figure 8.10: Extremum seeking with variable waste: Case 1. Cyan: Fixing $T_2 = 900\text{ K}$, $T_3 = 1350\text{ K}$; Red: Leaving T_2 and T_3 free to vary. Blue: $T_3 = 1350\text{ K}$, T_2 left free to vary; The target steam production is bound to lie in the interval $[37.5, 38.5]$. The waste composition varies with a time constant of 30 minutes and a filter time of 2 hours.

composition. The extremum seeking is faster for the second pile than for the third one, therefore most of the variation is compensated in this pile, as can be seen in Figure 8.14. The new reference temperatures are reached by varying the control input, as shown in Figure 8.15. The waste feed rate, though also a control input, does not vary relevantly. This is mostly due to the fact that the deadband on the height of the second pile is large, and the weight multiplying the error, see Chapter 7 is small. As different waste compositions show a maximum for different couples of T_2 and T_3 , as shown in Section 8.1, the steam target interval where we can expect to reach a maximal steam flow rate value varies as well. Nonetheless, since it is reasonable to assume that in an actual plant, no information is available beforehand on the composition of the waste coming in the next hours, during the tests here described the steam target interval has been kept constant. Maintaining the steam interval constant, and keeping the same actuators' constraints, means that it is possible that for certain waste compositions α it is not possible to find an input vector u such as the steam lays in that interval. The extremum seeking routine in these tests uses the parameters listed in Table 8.1.

The previous results have been obtained without imposing any constraint on the temperature in the combustion chamber. According to [7] the temperature in the combustion chamber must reach 850°C , (1100°C if hazardous wastes with a content of more than 1%

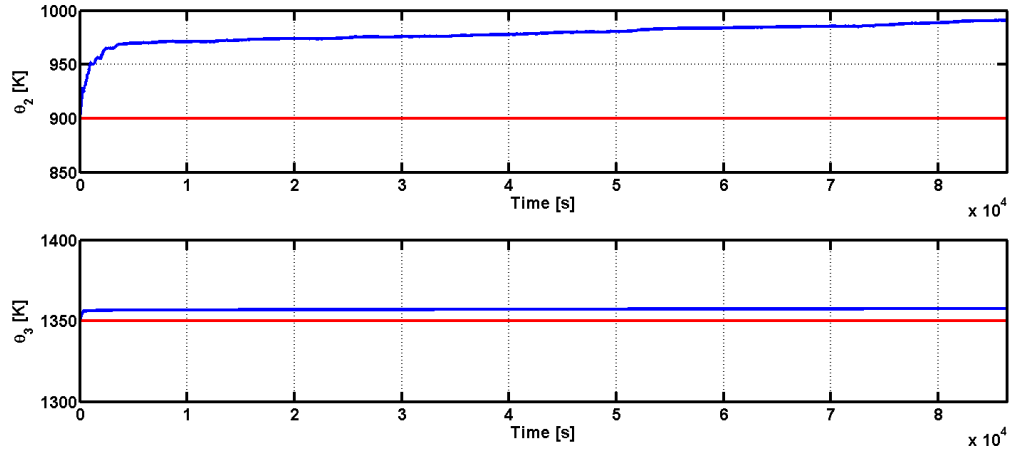


Figure 8.11: Extremum Seeking with variable waste composition: Case 1. The initial reference values for T_2 and T_3 , in red, are plotted against the output values θ of the extremum seeking, in blue.

<i>Case 1 : Pile₂</i>		<i>Case 1 : Pile₃</i>		<i>Case 2 : Pile₂</i>		<i>Case 2 : Pile₃</i>	
k_1	1	k_1	0.5	k_1	1	k_1	0.5
k_2	2.5	k_2	0.2	k_2	2.5	k_2	1
k_3	1.1	k_3	0.2	k_3	1.1	k_3	1
k_4	1.5	k_4	0.5	k_4	1.5	k_4	0.5

Table 8.1: ES Parameters for the test with variable waste test. The parameters have the meaning as in Figure 8.2.

of halogenated organic substances, expressed as chlorine, are incinerated), for at least two seconds. A further step could be to determine the waste bed temperature setpoints and the oxygen setpoint such as to maintain the prescribed temperature in the combustion chamber.

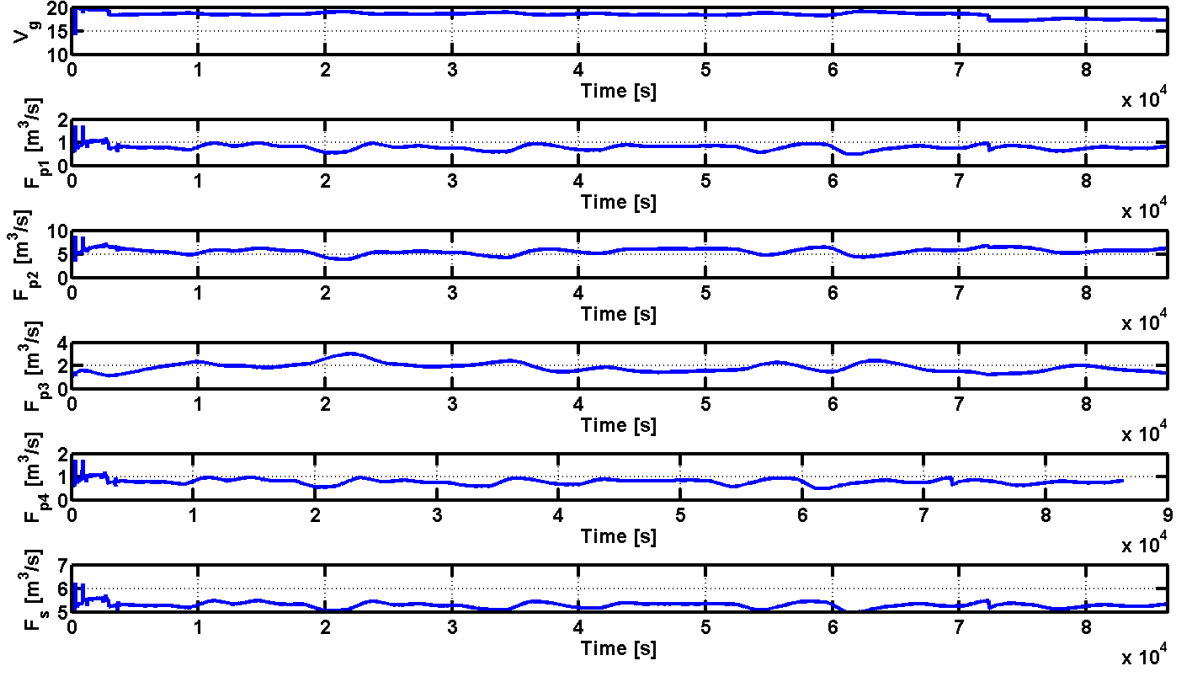


Figure 8.12: Extremum Seeking with variable waste composition: Case 1. The temperature of the waste bed for the second and third pile is kept to a target value by changing the speed grate V_g , the primary air flow rate F_p and the secondary air flow rate F_s .

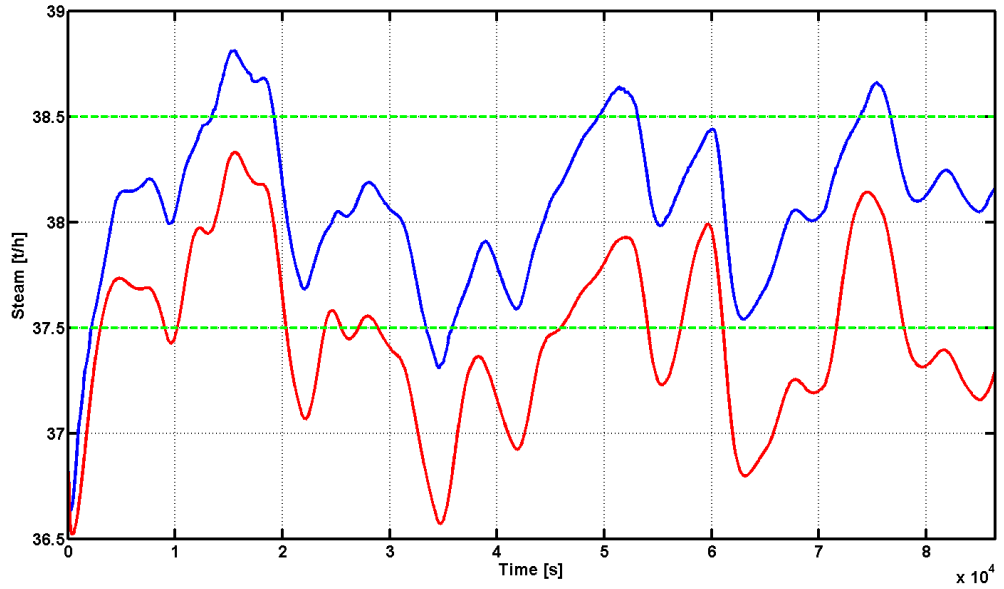


Figure 8.13: Extremum seeking with variable waste: Case 2. Red: Fixing $T_2 = 900\text{ K}$, $T_3 = 1250\text{ K}$; Blue: Leaving T_2 and T_3 free to vary. The target steam production is bound to lie in the interval $[37.5, 38.5]$, plotted with a dashed green line. The waste composition varies with a time constant of 30 minutes and a filter time of 2 hours. The waste has the LHV shown in Figure 8.9.

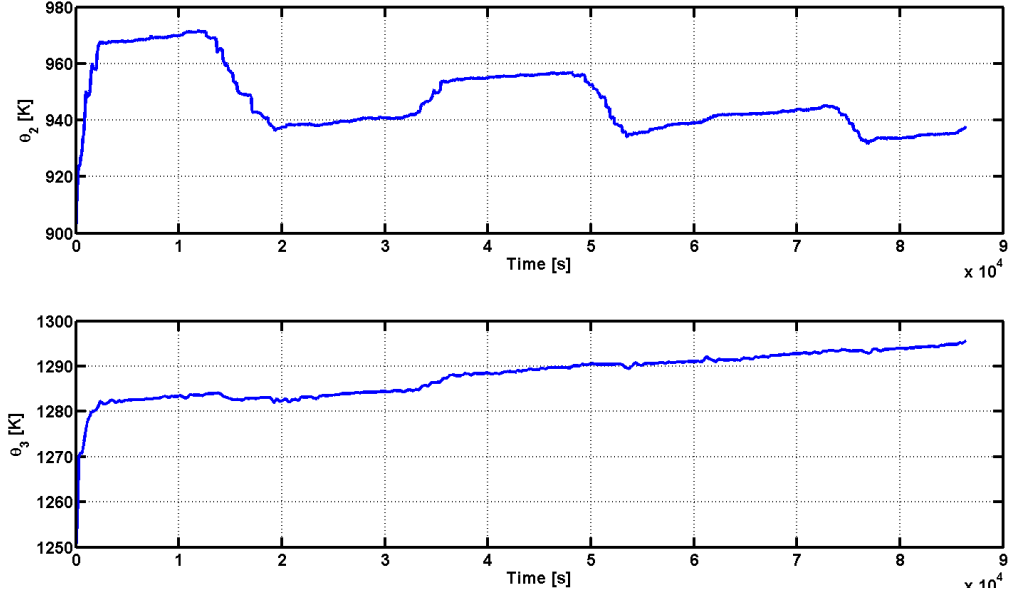


Figure 8.14: Extremum seeking with variable waste: Case 2. The initial reference values for T_2 and T_3 , in red, are plotted against the output values θ of the extremum seeking, in blue.

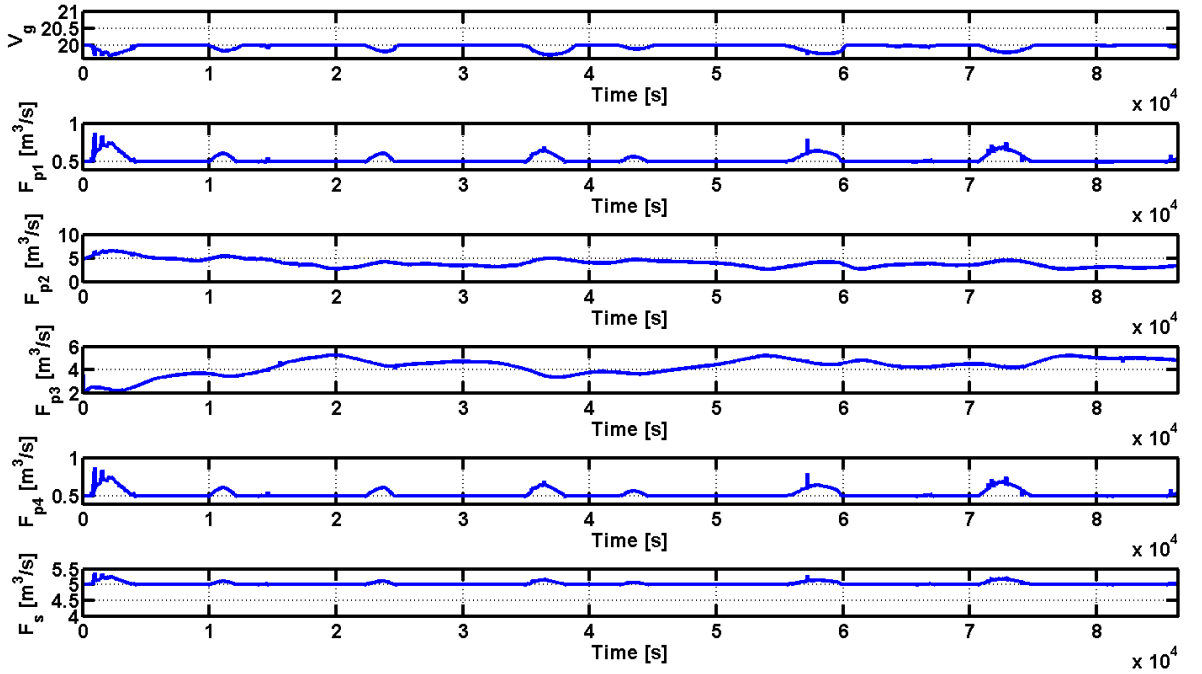


Figure 8.15: Extremum Seeking with variable waste: Case 2. The temperature of the waste bed for the second and third pile is kept to a target value by changing the speed grade V_g , the primary air flow rate F_p and the secondary air flow rate F_s .

Chapter 9

Conclusions

The aim of the study hereby presented is to identify new approaches in the control of the waste incineration process. The waste incineration process, described in Chapter 3 and Chapter 4 has always proven complicate to control, due to the high variability in heating value and humidity of the waste, Chapter 2. In the past years there has been a renewed interest in the modelling and control of the waste incineration process due to the increasing need for cheap electricity and for combustibles with net zero CO_2 emissions. A brief survey of the latest modelling and control approaches can be found in Chapter 1. In order to test new control and optimization strategies, a nonlinear model for the waste incineration on moving grates have been developed and validated at ABB Power Automation (CHPAU) and ABB Reaserch Center (CHCRC) in Switzerland [4]. The model relies strongly on a rigorous description of the main thermochemical processes taking place in an incineration plant, while being simple enough to be run in real time or faster. Under the reasonable assumption that a waste temperature measurement is available, first we have studied the possibility of finding a regression such as it is possible to express the steam flow rate S as a linear function of some inputs and states of the system. The regression parameters θ are estimated using the Recursive Least Square Method. The solution has been tested on the model and patented [43]. The second part of the study focuses on the possibility of finding a feedback linearization that can control the system to a set of reference values and then to define the reference set so that certain outputs are maximized. This is done via means of input/output linearization, Chapter 7 and extremum seeking Chapter 8. The input/output linearization has proven to be a valid approach to control the process to certain target values. Moreover it has shown to be robust against changes in the waste composition. The extremum seeking has also proven succesfully, succeeding in identifying target values for the waste bed temperature in the second and third pile such as the steam flow rate is maximized.

Nonetheless, given the actuators's constraints, instead of trying to find a maximal value for the steam we have decided trying to bring the steam flow rate to lie within a certain range. This is done by minimizing a (pseudoquadratic) cost function.

Possible next steps are for the introduction of further optimization loops, such as one for the oxygen target value in the flue gasses and the inclusion of the actuators' model. The control approach should then ideally be tested on an existing waste to energy plant.

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