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OPTIMIZATION OF GASIFICATION OF WASTE MATERIALS IN GRATE SYSTEMS

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ABSTRACT

The heavily sub-stoichiometric processing (gasification) in grate systems requires a clear separation of the steps for conversion of solid matter in the grate unit and postcombustion of the produced gases in the combustion chamber. In contrast to the conventional incineration process, this separate processing yields a number of advantages by employment of primary measures, like for example a decrease of flue gas and reduction of pollutants (CO, CH_x, NO_x,C_xH_y). In this context, this article presents some results from tests at a pilot plant.

KEY WORDS

Thermal waste treatment, grate systems, incineration, gasification, postcombustion, experimental research, pilot plant.

CONTENTS

1 INTRODUCTION

Stoker firing systems are frequently applied for incineration processes in the field of thermal waste treatment. Regarding reduction of pollution concentrations, the emphasis lay on the development of an efficient purification of flue gas and the post-treatment of residuals (i.e. secondary measures). Currently equipped plants now generally comply to the legally required limits concerning the discharge or the disposal of noxious matter in air, water and soil.

Further reduction of stack emissions is expected by optimizing the thermal process by primary measures. With the objectives to reduce the flue gas, to minimize pollutants and to influence the properties of the solid residues, current developments in the area of the conventional processing with grate technology indicates a considerable potential for optimization. The optimization of the combustion chamber design, the flue gas recirculation and mixing of flue gas, oxygen enrichment of the primary air, water-cooled grate elements and further development of control systems (e.g. IR-camera) are examples in this context [1 to 8].

With regard to an independent control of the conversion of solid matter and the incineration of the gases produced, a clear separation of grate unit and postcombustion chamber is required. The measures can be employed for the full-scale control of the influencing parameters (table 1: temperature, oxygen supply, reactor behaviour, residence time, etc.) by clearly separating the processes. Many possibilities of optimization exist for this multi-staged process operation with

- gasification with air on the grate followed by
- an independent postcombustion of the gases generated.

First of all, explanation of focal points and objectives of the gasification-postcombustion processing and description of the pilot plant is given here briefly.

With reference to test results concerning the gasification of waste wood, special emphasis lays here on the composition of the generated combustible gas effected by the staging of the air supply along the grate path, loss on ignition of the remaining residuals and flue dust discharge.

Concerning independent postcombustion of the gases generated in the grate process, the minimization of NO_x-emissions with simultaneously low-CO-emissions by air staging is examined.

2 GASIFICATION-POSTCOMBUSTION PROCESS

A concept of thermal treatment of waste should guarantee a low level of pollutants. Before secondary measures are expanded further, the main thermal processes must be optimized above all by primary measures. The process conditions are chiefly determined by the level of main influencing parameters (table 1) and the distribution of these parameters along the reaction path is important together with the different reaction steps.

From the technical point of view of the combustion process, coarse waste materials are more difficult to treat than regular gaseous, liquid and powdered fuels. For very different successive tasks, like:

- conversion of solid matter and
- combustion of gases generated,

the separation into different process units provides opportunities for individually optimizing each task. To minimize flue gas heat loss and total flow rate and in order to avoid carbon loaded residuals, the solid combustibles should be gasified in the first unit. The gas generated in this way can then be independently burned in the second unit with a low total excess air ratio and without additional fuel. A further precondition for optimization of waste incineration is given by the separation of reaction processes and heat transfer. To achieve hot walls in gasification- and combustion-mode, nearly adiabatic conditions are necessary due to the low calorific value of waste materials. If there is no heat transfer and intensive mixing is realized, the reaction conditions are uniform and a freezing of reactions can be avoided.

Measures to control the process include air staging, air preheating, oxygen enrichment and flue gas recycling. The possibilities to control the main influential parameters are closely connected with the respective devices applied [9, 10]. For coarse waste materials grate systems, rotary kilns, fluidized bed reactors and shaft furnaces are used. There are many possibilities available with grate systems for controlling the main acting variables (table 2). In contrast to shaft furnaces, rotary kilns and fluidized bed reactors, grate systems enable a control of reaction steps (drying, degassing, gasification, burn-out) over the reaction path.

Gaseous, liquid and powdered fuels are mostly burned in combustion chambers (table 2).

The way of conducting the processes

- gasification of solid matter on the grate with air ($\lambda_g \approx 0.4$ to 0.8),
- postcombustion of the gases almost stoichiometrically ($\lambda_{tot} \approx 1.2$ to 1.4) and
- heat exchange

separately, is shown schematically in figure 1. This gasification-postcombustion concept, currently examined on a test-size scale, appears promising, as, in comparison to the conventional incineration processing in grate systems,

- the flue gas mass flows are significantly reduced,
- combustible gases which enable an independent postcombustion process are generated,
- the postcombustion process itself can be optimized regardless of the process on the grate with the help of familiar primary measures for reducing the NO_x-emissions and at the same time achieving high burn-out results,
- emission loads can be reduced considerably.

These aspects are now explained in detail, with reference to first results at a pilot plant.

3 PILOT PLANT

The flow diagram of the pilot plant, including the scheme of the corresponding process measuring and control equipment, is presented in figure 2. The plant consists of the main components

- 5-zone reverse acting grate or, alternatively, 3-zone advancing grate,
- combustion chamber system,
- heat exchanger and
- flue gas purification unit.

Within the framework set here, the essential aspects are briefly outlined. Complete details on plant technology, data logging system and analysis are reported elsewhere [11].

- The model combustible solid or waste material is supplied in intervals to the first grate zone via a feeding ram located at the lower end of the feeding hopper.
- The velocity of the grate elements is individually adjustable in the five grate zones.
- The reaction gas (usually air; recycling of flue gas or oxygen enrichment is possible) is supplied to the underside of the grate. It is also individually adjustable in the five grate zones regarding mass flow and oxygen concentration.
- The combustion gas generated in a sub-stoichiometrical operation of the grate process (gasification) is fed to the combustion chamber unit for an independent, multi-staged postcombustion.
- Depending on the primary measures to be examined in the area of the combustion chamber unit, a staging of the air and, if necessary, of the combustible can be provided for the setting of the required conditions of temperature, oxygen-concentration and residence time along the reaction path.
- The combustion air or, respectively, the recycled flue gas is supplied radially and/or tangentially. For reasons of clarity, only three inlet points for the combustion air and one for the recycled flue gas are marked in the plant diagram (figure 2).
- The scheme of the process measuring and control equipment in the flow diagram in figure 2 gives an outline of the quantities measured during the test operation.
- The measurements of gas components relevant for evaluating the gasification and combustion processes were made continuously and included NDIR CO, CO_2, paramagnetic O_2 and heat conduction H_2.
- The concentration of flue dust is measured discontinuously after isokinetic sampling by gravimetric method.
- NH_3 was measured discontinuously using an 0.1 N H_2SO_4 spray probe followed by a series of gas bubblers. Sample solution were analyzed photometrically.

4 GASIFICATION ON THE GRATE

Figure 3 shows schematically the conversion steps of solid matter in grate systems: drying, degassing, ignition, gasification and burn-out of carbon. In contrast to shaft reactors normally applied at gasification processes, these steps do not take place successively and/or overlappingly over the height of the bed but rather over the length of the reaction path. This has the advantage that regarding the objectives the steps can be essentially optimized separately one from each other.

The objectives in the first process unit, i.e. gasification on grate, are:

- minimization of carbon content in the ash and
- generation of combustible gas that enables a self-sustained postcombustion.

Using grate systems, several methods are available to achieve these objectives:

- adjustment of the absolute (integral) stoichiometric air ratio λ_g via the total mass flow of air,
- adjustment of the local stoichiometric ratios $\lambda_{g,l}$ via the appropriate staging of air,
- residence time and residence time distribution influenced by the motion of the grate elements.

As reported elsewhere [11], the combustible gas composition differs from values resulting from balance calculations. The major combustible component is found to be carbon monoxide ($\psi_{CO} \approx$ 8..15 vol.-%). The hydrogen content ($\psi_{H2} \approx$ 2..5 vol.-%) is far below the calculated equilibrium concentration. This may be attributed to the fact that the water content in the combustible evaporates at the beginning of the grate (figure 3). Thus, heterogeneous decomposition reaction between steam and the hot coke bed is not normal in conventional grate systems. Further, the equilibrium of the homogeneous reaction of CO and H_2O forming CO_2 and H_2 is not attained. Based on the assumption that the CO formation in the combustion bed of a grate essentially takes place via the heterogeneous gasification reaction of carbon with oxygen and, depending on the height of the bed, additionally via the so-called Boudouard-reaction, a hot coke bed should follow soon after the successful ignition of the combustible. Due to the decreasing carbon content along the length of the grate, less reaction air is required in the succeeding grate zones for gasification. This fact is confirmed by the results presented in figure 4. For evaluating the influence of air staging, three distinctly different air distribution settings (in each case with constant mass flows for both fuel and total air) have been tested. The main air supply is in zone 1 for the first setting and in zone 4 for the second. An even distribution over the zones 1 to 4 is approached for the third setting. Figure 5 shows the levelling off of hydrogen and methane concentrations to behave more or less independently from the selected air staging settings. The wood used as a model fuel already ignites in the first stage of the grate. When shifting the main air supply from the beginning to the end of the grate, the CO-concentration in the combustion gas is reduced. However, an increase of the grate bar velocity, which leads to a more intensive mixing and stoking of the combustion bed, causes an increase of the CO-concentration in the example given (figure 4).

The distribution of air depends on the fuel or waste material gasified. Refuse-derived fuel (RDF) with a significant content of synthetic material requires careful degassing and ignition (figure 5). Supplying the main part of air at the beginning of the grate causes the degassing products to be burnt immediately. This leads to high temperatures of the bed and consequently to a caking and fritting of the bed. An even flow through the bed is hindered.

As for incineration, residual carbon contents ξ_C of about 1 % or less (by mass) can be attained with gasification conditions; thus, coke-like solid residues are avoided. As an example, results of combustion and gasification of wood from railway sleepers treated with coal tar (contaminated, and, thus, waste wood of no further use) are shown in figure 6. In the context of the remaining burn-out of the ash it must be mentioned at this point that with an overall sub-stoichiometrical operation of the grate process (gasification), locally super-stoichiometrical conditions regarding the remaining carbon can nevertheless be adjusted in the area of the burn-out zone, if required.

Marked differences result between process conditions of the gasification and incineration mode with regard to the forming of flue dust. The significantly lower mass flow of air resulting from the operation under gasification conditions compared to those resulting from the super-stoichiometrical operation effects corresponding reduced flow velocities through the combustion bed. The expected tendency, that a decreasing stoichiometric ratio causes a reduced formation of flue dust, is confirmed in figure 6.

5 POSTCOMBUSTION PROCESS

The gases generated by gasification in the grate process are supplied to the postcombustion chamber. The heating value is about $h_u \approx 1500$ kJ/kg to $h_u \approx 2500$ kJ/kg and temperatures reach levels of $\vartheta \approx 750$ °C up to $\vartheta \approx 1000$ °C depending on the stoichiometrical air ratio of the grate process. If the postcombustion chamber is well insulated with a refractory jacket, the postcombustion process runs independently without additional fuel. Thereby well known primary measures to minimize pollutants can be applied [e.g. 12 to 16].

Consideration is given here to NO-minimization with a simultaneous reduction of CO-concentrations. First of all, the stoichiometrical ratio of the gasification process affects the NO emission.

Figure 7 shows the NO- and CO-emission of a staged combustion of the combustible gas generated at the grate by primary air ratio of $\lambda_G \approx 0.4$ and $\lambda_G \approx 0.6$. For the higher primary air ratio significantly lower NO-emissions are obtained. The increasing of primary air ratio is accompanied by an increase of temperature from about 700 °C to about 1000 °C. Further, an increase of oxygen supply results. With this, a higher decomposition of volatile nitrogen components like HCN and NH_i via NO and a reduction of already formed NO via the "NO-recycle" path is more probable.

Next to the influence of the primary air ratio, the NO-concentrations in figure 7 show the typical course for the formation of NO from the nitrogen contained in the fuel. The NO-concentrations decrease with a falling air ratio in the first stage of the combustion chamber whereby the total air ratio is kept constant $\lambda_{tot} \approx 1.3$. For a primary air ratio of about $\lambda_G \approx 0.4$, the NO-concentration drops from about 450 mg/m^3 for a single-staged postcombustion to 200 mg/m^3 for a twofold-staged postcombustion (air supply in stage I and II) with $\lambda_{PC\ I} \approx 0.5$, whereby the CO-concentration is far below 10 mg/m^3. In the same manner the NO-concentration can be reduced in the case of a primary air ratio of $\lambda_G \approx 0.6$, from 200 mg/m^3 to about 120 mg/m^3.

For a twofold-staged postcombustion, a further NO reduction below 100 mg/m^3 results when feeding air to the first and the third stage of the combustion chamber (figure 8) whereby the CO-concentration remains below 10 mg/m^3. The further NO reduction here is due to the longer residence time in connection with higher temperatures and lower oxygen concentrations in the sub-stoichiometrical first stage.

Figure 9 shows the influence of air staging and the influence of total air ratio on the NO- and CO-concentrations for a twofold-staged postcombustion with air supply at position I and III. As expected, the NO-concentration decreases with a falling total air ratio. The reduction of the NO-concentration from about 450 mg/m^3 to 150 mg/m^3 seems possible with a simultaneously low CO-concentration below 10 mg/m^3. A further reduction of NO below 100 mg/m^3 is connected with an increase of CO from below 10 mg/m^3 to about 40 mg/m^3. In addition to this, CO peaks appear at total air ratio $\lambda_{tot} < 1.2$ more often than with a higher air ratio due to variations of the composition of the combustible gas. This may be caused by feeding intervals of the grate unit. These peaks can be buffered with a corresponding supply of additional air when this phenomenon appears. However, tests presented here were carried out without any automatically control.

Furthermore, the influence of load variations of the fuel supplied to the grate on the NO- and CO-concentrations were investigated. Figure 10 shows the results of test runs, carried out with normal load (60 kg/h) and overload (80 kg/h, 100 kg/h). Thereby the primary air ratio and the total air ratio were kept constant $\lambda_G \approx 0.4$, $\lambda_{tot} \approx 1.3$. The increase of the mass flow rate of fuel to the grate leads to an increase of the NO-concentration for a twofold-staged postcombustion process. Similar to the procedure mentioned above, air staging leads to a significant reduction of NO from 450 mg/m^3 to about 200 mg/m^3 for overload conditions too. Thereby CO-concentrations do not exceed levels of about 20 mg/m^3.

Further investigations concerning the optimization of the gasification-postcombustion process are ongoing. There are still questions which have to be examined in detail. They concern experimental investigations such as the influencing of the ash elution behavior, for example, as well as mathematical modeling.

6 ACKNOWLEDGEMENTS

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7 NOMENCLATURE

SYMBOLS

h	specific enthalpy
ϑ	temperature
λ	air ratio, stoichiometric ratio
ξ	concentration (mass related)
ψ	concentration (volume related)
ω	frequency

INDICES

C	carbon
EG	exhaust gas
f	fuel
g	grate
G	combustible gas
HD	hydraulic pump
i.s.s.	in standard state
l	local
m	mass
mes	measured parameter
n	net (h_n net calorific value)
pc	postcomustion chamber
re	remnants
RG	reaction gas (air)
tot	total
·	flux

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9 TABLES AND FIGURES

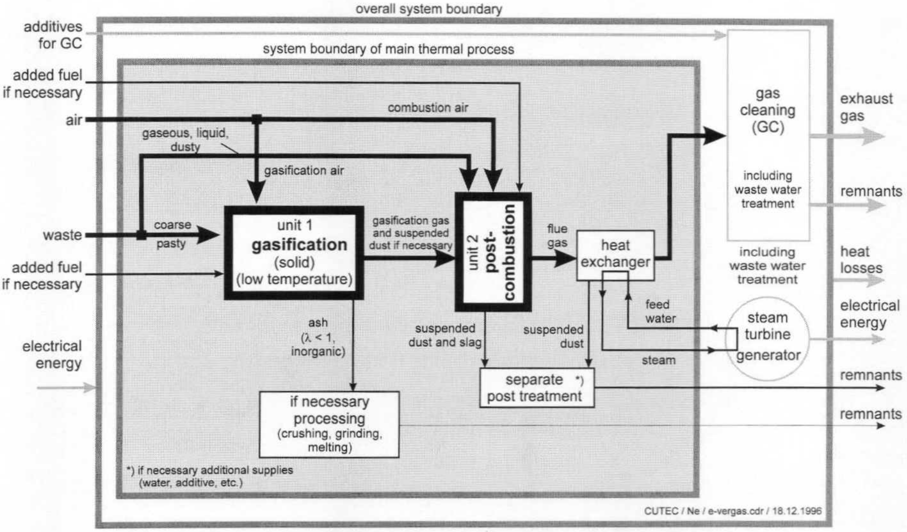

Figure 1: Block flow diagram for gasification - postcombustion process.

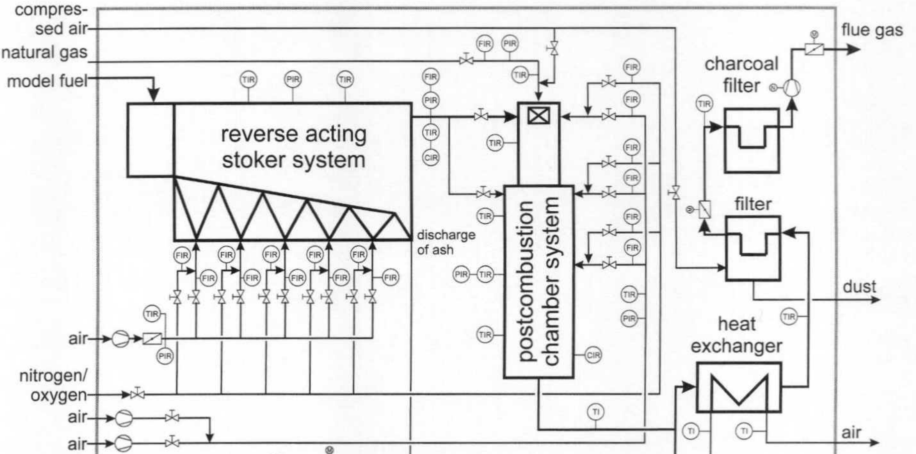

Figure 2: Process scheme of the pilot plant; reverse acting stoker system and independent postcombustion chamber.

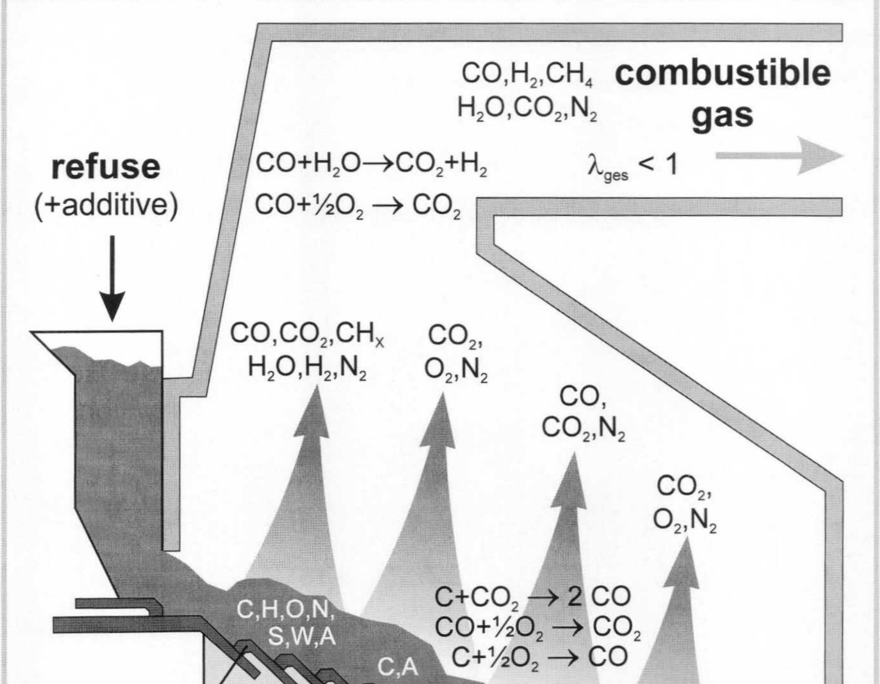

Figure 3: Combustion steps of a stoker firing system.

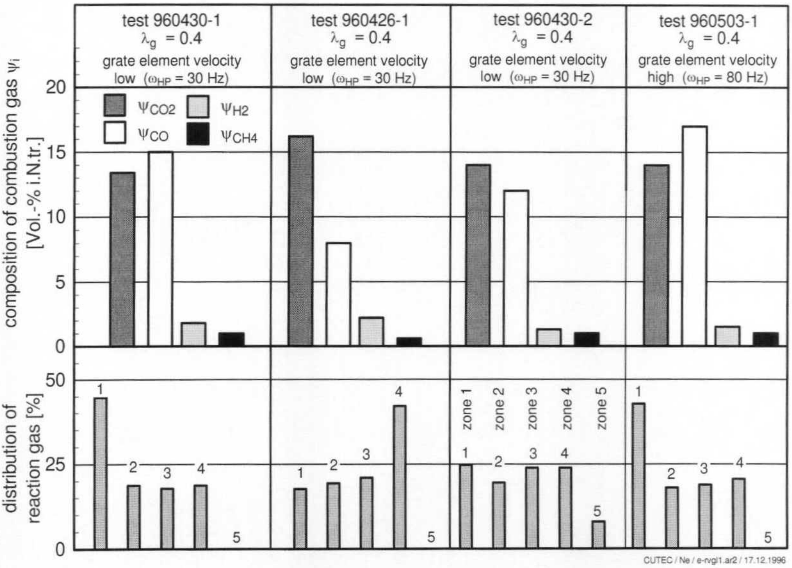

Figure 4: Comparison of the composition of combustion gas with varying distribution of reaction gas along the grate path and grate element velocity (model fuel wood).

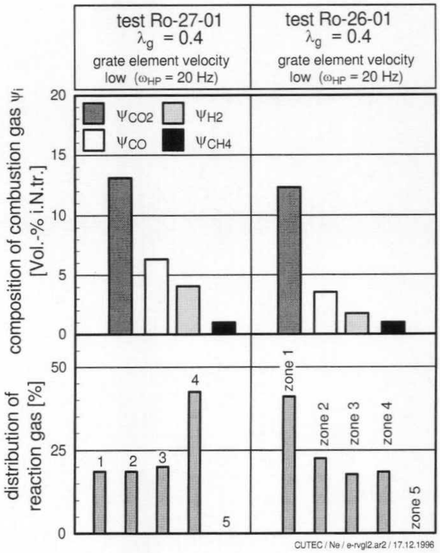

Figure 5: Comparison of the composition of combustion gas with varying distribution of reaction gas along the grate path (refuse-derived fuel RDF).

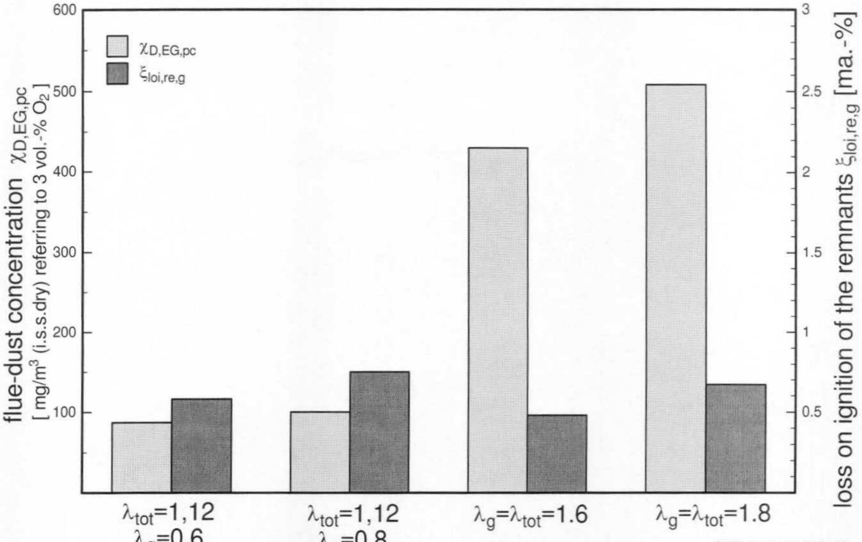

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Figure 6: Flue-dust concentration before flue gas cleaning and loss on ignition for different stoiciometrical ratios in the stoker system

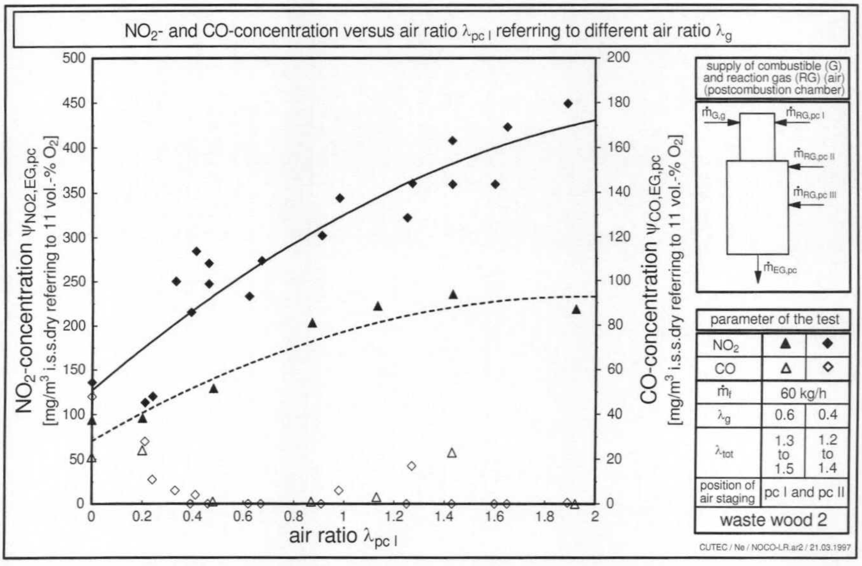

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Figure 7: NO₂- and CO-concentration versus air ratio $\lambda_{pc\,I}$ (different air ratio λ_g in the grate unit).

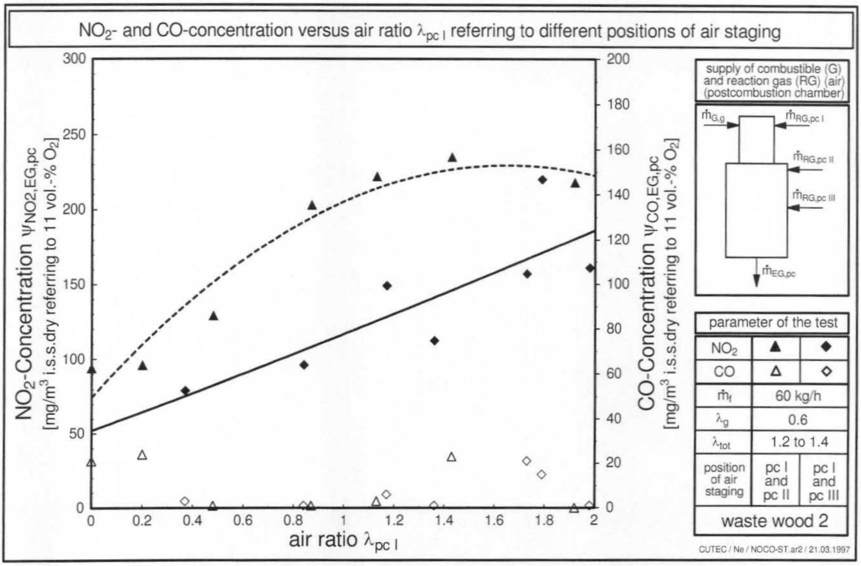

Figure 8: NO_2- and CO-concentration versus air ratio $\lambda_{pc\,I}$
(different positions of air staging in the post combustion chamber).

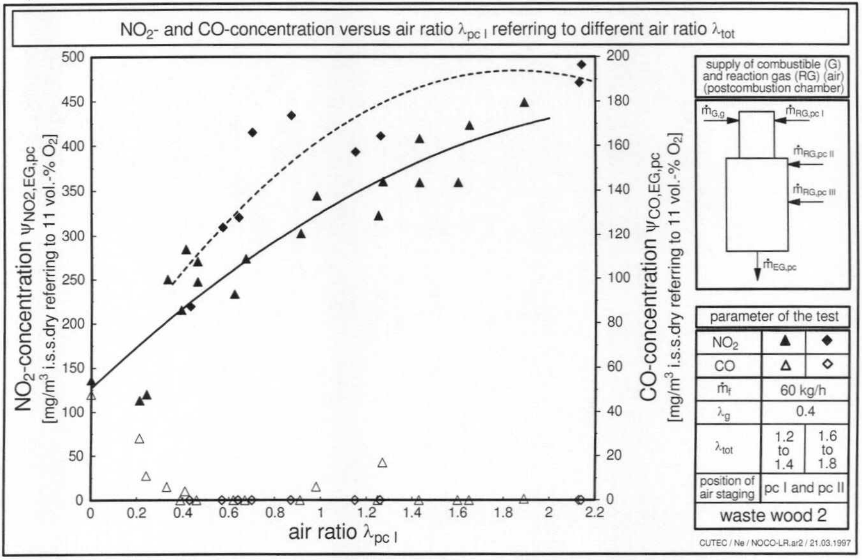

Figure 9: NO_2- and CO-concentration versus air ratio $\lambda_{pc\,I}$
(different total air ratio λ_{tot}).

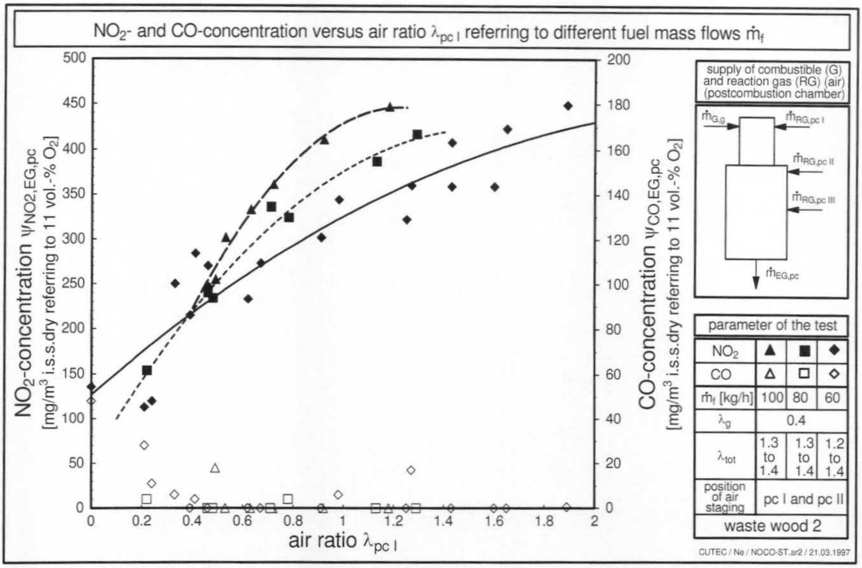

Figure 10: NO$_2$- and CO-concentration versus air ratio $\lambda_{pc\,I}$ (different fuel mass flows in the grate unit).

waste materials	**physical properties**	gaseous, liquid, pasty, solid (dusty or coarse)		
	chemical properties	composition (problematic substances)		
oxygen supply	**thermolysis** $\lambda = 0$	**gasification** $\lambda < 1$	**combustion** $\lambda \geq 1$	
reaction gas	air, oxygen, (nitrogen), carbon dioxide, steam, recirculated flue gas, etc.			
temperature	**low** $\vartheta < 600\ °C$	**until**	**high temperature** $\vartheta > 1000\ °C$ (up to 2000 °C and higher)	drying, degassing, melting, evaporation, sublimation
pressure	**low pressure** p « 0,1 MPa	**atmospheric pressure** p ≈ 0,1 MPa	**high pressure** p » 0,1 MPa	
reactor behavior	**continuous stirred reactor (CSR)** Pe = 0	**real reactor** 0 < Pe < ∞	**plug flow reactor (PFR)** Pe → ∞	
method of material input	**feed momentum, swirl, atomization, disperse, etc.**	for e.g. waste materials, reaction gas, additional substances		
residence time	**short** several s	**long** several min up to hours	**very long** several hours up to days	
additional substances	**additive** (e.g. bonding of pollutants, controling the melting behavior) **additional fuel** **bed** (e.g. fluidized bed, solid bed, circulating bed, binding matrix, ash feedback)			

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Table 1: Main influencial parameters for thermal treatment.

Apparatus:	Grate Systems
	Substances Treated
	Lumpy or pasty when mixed with a solid or inert bed
	Oxygen Supply
level	Usually overstochiometric (combustion); understoichiometric (gasification) with self sustaining post-combustion possible; in the absence of oxygen (pyrolysis) not customary.
control along reaction path	Easily adjustable in the separate zones (e.g. air/oxygen staging, fluegas recycling etc.). The partial steps: drying, devolatilisation, gasification and burnout of remaining solid can be influenced.
	Temperature
level	Bed surface temperature up to approximately 1000 °C and higher; medium bed temperature is lower.
control along reaction path	Sufficient possibilities through division into zones, as in the case of control of oxygen concentration (air preheating, fluegas recycling, water/steam cooling).
	Pressure
	Few Pascal lower than ambient pressure, due to technical reasons.
	Reactor Behaviour
solid	Depending on grate movement, the zones can be considered as a CSR (e.g. reverse acting grate) or PFR (e.g. travelling grate). PFR characteristics are approached over the total reactor length.
gas (in the bed)	Oxidants are forced through the bed and are evenly distributed over bed surface. Very good contact between gas and solids result.
gas (above the bed)	Counter current and co-current flows above the bed are possible. Gas treatment is neccessary in process steps that follow (e.g. post-combustion).
	Residence Time
level (average residence time)	Ranging from minutes to hours. Adjustable through grate movement speed, mass flow rate and design dimensions (length and width).
control along reaction path	Good adaptation is possible through speed adjustments in the grate elements of the separate zones. Burnout at the end of the grate can be improved, if neccessary, with control of the discharge roll.
	Additional substances
	Additives for absorption of pollutants into the solid and control of residue properties (ash, partially molten ash, slag). Inert beds e.g. binding matrix for low melting substances such as plastics.
	Applications
	For conversion of solids in the first stage of household waste combustion. Low temperature separation of metals from composite materials with understoichiometric conditions.

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Table 2: Characteristics of grate systems.