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GASIFICATION OF WASTE MATERIALS IN GRATE SYSTEMS

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THIS ARTICLE IS DEDICATED TO PROFESSOR DR.-ING. W. LEUCKEL ON HIS 65TH BIRTHDAY

ABSTRACT

The separate conduction of a thermal process by gasification in a grate system and a following combustion chamber system results various possibilities for an independent optimization of the conversion of solid matter in the grate and the postcombustion of the generated gases. In the article these possibilities are presented by experimental results of a pilot plant (max. thermal power 0,5 MW).

KEY WORDS

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

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1 INTRODUCTION

For decades grate systems have been employed for the thermal treatment of household waste and similar wastes from industry. With regard to the 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). Plants equipped now according to the state of the art generally comply with the legally required limits concerning the discharge or the disposal of noxious matter in air, water and soil.

The developments of the past few years in the area of the conventional processing with grate technology indicate a considerable potential for optimization through so-called primary measures. 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) can be mentioned here [1 to 8]. Furthermore, many possibilities of optimization exist for multi-staged process operation with

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

The paper describes the testing of the multi-stage gasification-postcombustion concept on a pilot plant.

First of all, general aspects of the operation of this process concept are explained in brief.

The gasification process on the grate is dealt with reference to test results. Special emphasis is given 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, release of heavy metals and flue dust discharge.

In the context of independent postcombustion of the gases generated in the grate process, the minimizing of NO_x-emissions with simultaneous low-CO-emissions by air staging is examined. The PCDD/F-concentrations at postcombustion temperatures of $\vartheta_{ac} \approx 1300$ °C and $\vartheta_{ac} \approx 950$ °C are presented, too.

2 CONCEPT OF GASIFICATION-POSTCOMBUSTION WITH GRATE SYSTEMS

Regarding the thermal treatment of coarse waste one has to distinguish in principle between the separate tasks relevant to the conversion of solid matter and those relevant to the conversion in the gaseous phase. Different process conditions are necessary, determined by the values of the main acting variables (oxygen concentration, temperature, residence time and residence time distribution), for the optimization of these two different processes and the special tasks belonging to the respective process. Therefore, it seems obvious to optimize processes independently in separate process units according to the given requirements. Additionally, sufficient possibilities should exist for controlling the main acting variables along the reaction path (e.g. air staging within a process unit). These possibilities for control are closely connected with the respective devices applied [9, 10].

The possibilities available with grate systems for controlling the main acting variables (table 1) can be applied particularly efficiently in terms of primary measures, when the process steps

- conversion of solid matter on the grate
- postcombustion of the gases generated on the grate and
- heat exchange

are positively distinct from one another, in contrast to the usual simultaneous occurrence of these processes. This way of separating the processes, shown schematically in figure 1, enables running the solid matter conversion on the grate (first unit) in the heavily understoichiometrical range of $\lambda_g \approx 0.4$ to $\lambda_g \approx 0.8$. The generated gases are burned independently and almost stoichiometrically in the following postcombustion chamber. This gasification-postcombustion concept, currently examined on a test-size scale, appears promising, as, in addition to the advantages of an independent process conduction,

- 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 for achieving simultaneous high burn-out results,
- emission loads can be reduced considerably.

In the following, these aspects are detailed in the context of pilot-plant test-results.

3 PILOT PLANT

Figure 2 presents the flow diagram of the pilot plant including the scheme of the corresponding process measuring and control equipment. The plant consists of the main components

- 5-zone reciprocating 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, while further details on plant technology, data logging system and analysis are explained in [11].

- The solid model combustible/ 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 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 incineration.
- 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, 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 gas components relevant to evaluation of the gasification and combustion processes (CO, H_2, CH_4, CO_2, O_2, NO) are detected continuously by NDIR, heat conduction or paramagnetic method.
- The concentration of flue dust is measured discontinuously after isokinetic sampling by gravimetric method.
- A sample of the filtered dust is dissolved (e.g. by microwave). The concentration of heavy metals in the solution is then determined by *ICP* or *AAS*.
- Nonfilterable and vapour forming heavy metals or compounds are retained with downstream solid sorbents (for example activated charcoal) or with absorption solutions (e.g. $KMnO_4$ solution) via a heated probe. After sample preparation the concentration of heavy metals is also determined by *ICP* or *AAS*.
- As known, the determination of *PCDD/F* in exhaust gas requires isokinetic sampling. A water cooled extraction probe is used in order to prevent reactions in the connecting joint. Depending on the situation, solid sorbents (e.g. activated charcoal, quartz filter) of absorption solutions (e.g. methoxy ethanol, water) are used. The determination of the respective absolute concentration takes place as usual, after proper sample preparation, with GC MS.

4 GASIFICATION ON THE GRATE

In the first unit of the process, i.e. gasification on the grate, two primary objectives are:

- minimization of the carbon content in the process residues,
- generation of a suitable combustible gas composition with the content of carbon monoxide being as high as possible.

For achieving these objectives the following methods can be applied:

- adjustment of the absolute (integral) stoichiometric ratio λ_g over the total mass flow of air supplied or, respectively, in connection with appropriately adjusted oxygen concentrations,

- adjustment of the local stoichiometric ratios over the appropriate staging of the air or reaction gas along the reaction path,
- influencing the residence time and the residence time distribution of the solid fuel by means of the motion of the grate elements

can be taken.

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. Figure 3 shows the results of different over- and understoichiometrical settings of the grate process, using the example of wood from railway sleepers treated with coal tar (contaminated, and, thus, waste wood of no further use) as an input material. In the context of the remaining burn-out of the ash it must be mentioned at this point that with an overall understoichiometrical operation of the grate process (gasification), locally overstoichiometrical conditions regarding the remaining carbon can nevertheless be adjusted in the area of the burn-out zone, if required.

Marked differences result in the forming of flue dust between the operation under gasification and incineration process conditions. The significantly lower mass flow of air resulting from the operation under gasification conditions compared to those resulting from the overstoichiometrical operation effects corresponding reduced flow velocities through the combustion bed. The expected tendency, that a decreasing stoichiometric ratio goes together with a reduced formation of flue dust, is confirmed in figure 3.

The influence of the staging of air and the motion of the grate elements on the composition of the combustion gas is shown in figure 4 in connection with results from tests with wood as a model combustible. For the evaluation of 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 4 shows the leveling off of hydrogen and methane concentrations to behave more or less independently from the selected air staging settings. Here, the hydrogen concentrations ψ_{H2} of about 2 vol.-% are far below the values resulting from balance calculations. As already discussed elsewhere [11], this may be attributed to the fact that the water content in the combustible is evaporated at the beginning of the grate. Thus, heterogeneous decomposition reaction between steam and the hot coke bed is not normal in conventional grate systems. The major combustible component is found to be carbon monoxide ($\psi_{CO} \approx 8..15$ vol.-%). Based on the assumption that the CO formation in the combustion bed of a grate takes place essentially 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. The wood used as a model combustible 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). Please note, however, that in this example the air mass flows are approximately equal in zones 2 to 4.

A further significant question when optimizing the process conditions in the grate stage is linked to the behaviour of heavy metals contained in the waste. Tests with mixtures of shredded light fraction (waste from shredder plants with mixed scrap) with wood provide some indications concerning this matter. Figure 5 shows the results of measurements of the heavy metal concentrations in the flue gas. Here, the operation under gasification conditions with $\lambda_g \approx 0.6$ and $\lambda_{tot} \approx 1.2$ is compared to the operation under incineration conditions with $\lambda_{tot} \approx 1.8$. Considering the total concentrations, the operation under gasification conditions shows a circa 70 % lower concentration in comparison to the operation under incineration conditions. As seen in figure 5, this reduction can be attributed to the drop in the flue dust content. Of interest seems to be, what effects the conditions of gasification have on the mobility of the heavy metals. The mobility is essentially influenced by the temperature conditions, the residence time and the contents of chlorine in the incineration bed [12, 13, 14]. The temperature and the residence time are adjustable via the process control, whilst the input of chlorine is determined by the composition of the waste material. When comparing the gasification and incineration operation modes with respect to the influence of chlorine, attention must be paid to the fact that, due to the lower gas mass flows, higher chlorine concentrations as well as longer residence times of the gases in the bed are to be expected with an understoichiometrical operation of the grate. Thus, considering the results in figure 6, the comparatively high non-particle-bound contents, particularly of lead and cadmium, occurring during the gasification operation mode can be attributed to an increasing volatility due to a higher chlorine concentration and longer residence times in the combustion bed. It must be stressed that these investigations provided first indications, and for further clarity a series of further investigations must be conducted concerning the fate of trace elements (e.g. elution behaviour).

5 INDEPENDENT POSTCOMBUSTION OF THE COMBUSTION GASES

The postcombustion of the combustible gases generated during the grate process takes place in an independent furnace. The combustion gases have a calorific value of about $h_n \approx 2000$ kJ/kg and are supplied to the postcombustion process at temperatures from $\vartheta \approx 750$ °C to $\vartheta \approx 850$ °C. The separation of the combustion process allows the independent optimization of the postcombustion process with regard to the reduction of noxious matters such as carbon monoxide, organic compounds and nitrogen oxides. The primary measures in question have been examined in the context of research on the combustion of gaseous, liquid and dusty fuels to such an extent that it should suffice to refer to the respective literature [e.g. 15 to 19].

In connection with the gasification-postcombustion operation mode, the possibility of

- minimizing nitrogen oxides at high burn-out (CO) is dealt with and the
- dependence of the PCDD/F concentrations in the crude gas on the postcombustion temperature is explored.

Again, the results presented are derived from examinations with contaminated wood waste.

As seen in figure 6, a first NO-reduction is achieved when conducting the process with a single-staged postcombustion of a combustion gas generated at stoichiometric ratios of $\lambda_g \approx 0.6$ and $\lambda_{tot} \approx 1.2$ as opposed to the NO-values of an overstoichiometric operation with $\lambda_g \approx 1.6$ and $\lambda_{tot} \approx 1.8$. A further significant measure to reduce the NO-emissions is to be found in the staged incineration (air staging in the postcombustion chamber). Regarding the reduction of the NO in the combustible, figure 6 shows the aforementioned relationship between the stoichiometric ratio λ in the first stage of the combustion chamber and the NO concentrations in the flue gas (raw).

As seen from the respective CO concentrations in figure 6, a constantly low level of $\psi_{CO} \approx 10\ \mathrm{mg/m^3}$ is attained with a staged conduction of the process in the postcombustion chamber. In total, the level of CO concentrations is significantly lower when conducting the process separately than with an overstoichiometrical operation of the grate system (figure 6).

Primary air ratios between $\lambda_g \approx 0.4$ and 0.8 result in overall air ratios (including secondary and possibly tertiary air) lower than $\lambda_{tot} \approx 1.2$ (cf. figure 6), which means a considerable reduction of the flue gas mass flow and, thus, of the noxious matter loads, is achieved compared to conventional plants.

Furthermore, it should be mentioned, that when decoupling the heat exchange from the postcombustion process and, with adequate insulation and lining of the combustion chamber with refractory material, postcombustion temperatures higher than those resulting from the conventional operation of the process (grate overstoichiometrical) are obtainable. This is mentioned, in case higher temperatures (e.g. 1200 °C) are legally required in connection with the handling of contaminated waste.

However, from the point of view of the incineration process and reaction process, when discussing the desirable level of temperature, all the main acting variables: temperature, oxygen concentration, residence time and residence time distribution (degree of mixing), in particular, should be considered together.

The PCDD/F results in table 2 demonstrate this interdependency of variables, referring to tests on the gasification with separate postcombustion in the pilot plant of mixtures of creosote-impregnated wood from railway sleepers and window wood (contaminated waste woods). The PCDD/F concentrations shown in table 2, measured at the exit of the combustion chamber unit, remain essentially at the same level, within experimental error, irrespective of the combustion chamber temperatures (950 °C to 1350 °C). All values lie considerably below 0.1 ng TE/m^3 i.s.s.dry. In the case presented, the results indicate that no immediate relationship exists between the temperature level alone and the PCDD/F concentrations. Thus, an isolated inspection of just one main acting variable, e.g. the temperature, proves insufficient.

6 ACKNOWLEDGEMENT

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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
g	grate
G	combustible gas
HD	hydraulic pump
i.s.s.	in standard state
loi	loss on ignition
mes	measured parameter
n	net (h_n net calorific value)
re	remnants
tot	total

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9 TABLES AND FIGURES

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 Pa 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 and 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 1. Characteristics of Grate Systems.

test no.			1	2	3	4
temperature in the afterburning chamber	ϑ_{ac}	[°C]	1 346	982	1 197	936
oxygen concentration (measured)	$\psi_{O2,mes}$	[vol.-%] i.s.s.dry	5,62	6,14	6,11	5,69
Toxicity-Equivalent (according to BGA 1)) (referring to $\psi_{O2,mes}$)	TE	[ng/m^3] i.s.s.dry	0,093	0,079	0,015	0,058
Toxicity-Equivalent (according to NATO/CCMS 1)) (referring to $\psi_{O2,mes}$)	TE	[ng/m^3] i.s.s.dry	0,079	0,056	0,011	0,036
Toxicity-Equivalent (according to BGA 1)) (referring to 11 vol.-% O_2)	TE	[ng/m^3] i.s.s.dry	0,060	0,053	0,010	0,038
Toxicity-Equivalent (according to NATO/CCMS 1)) (referring to 11 vol.-% O_2)	TE	[ng/m^3] i.s.s.dry	0,051	0,038	0,007	0,024

1) German limit according to Bundesgesundheitsamt (BGA)

2) International limit according to NATO/CCMS

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Table 2. Measured PCDD/F-concentration in the flue gas at a temperature of ϑ_{ac}=1300 °C and 950 °C.

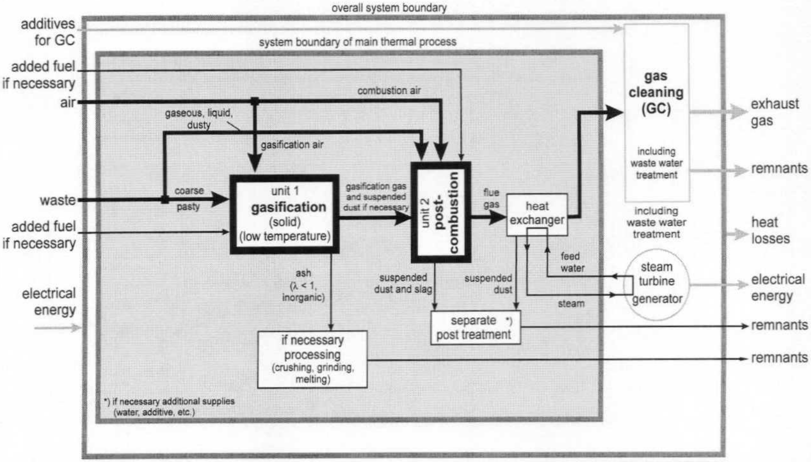

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Figure 1. Block flow diagram for gasification-postcombustion process; advanced standard waste incineration (household waste).

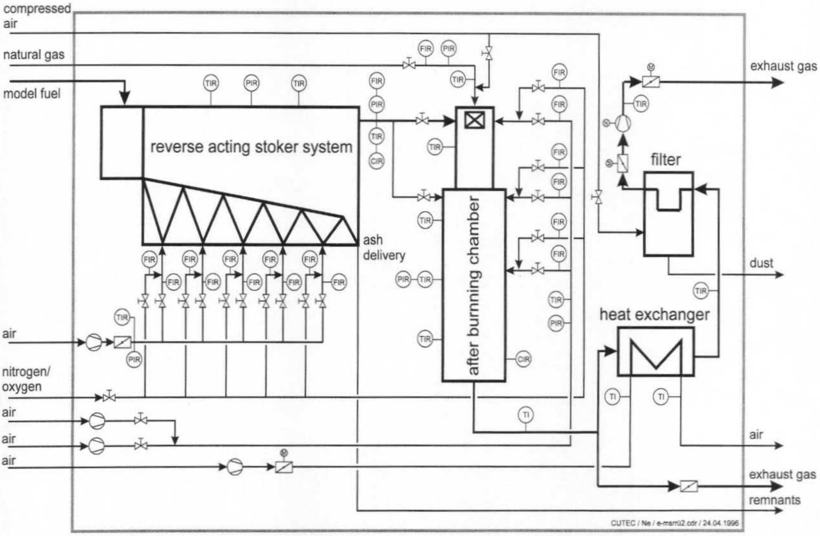

Figure 2. Process scheme of the pilot plant; reverse acting stoker system and independent afterburning chamber.

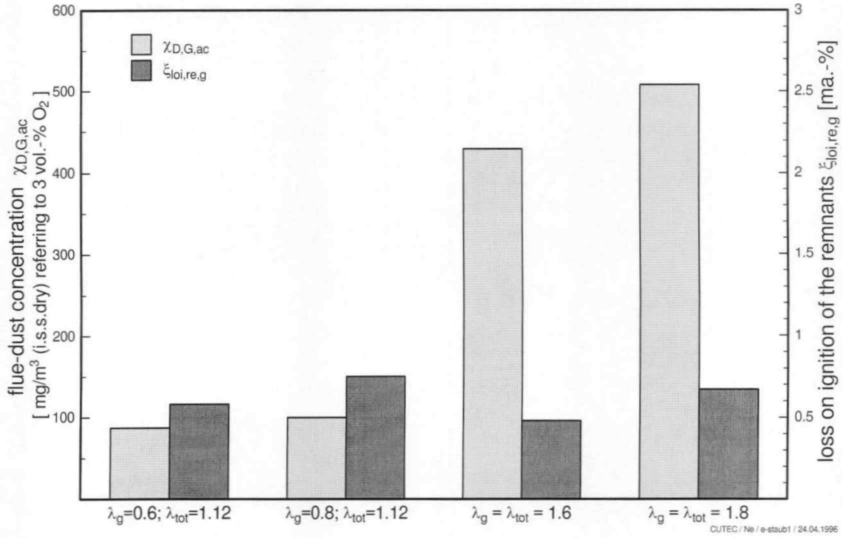

Figure 3. Flue-dust concentration before flue gas cleaning and ignition loss for different stoichiometrical ratios in the stoker system.

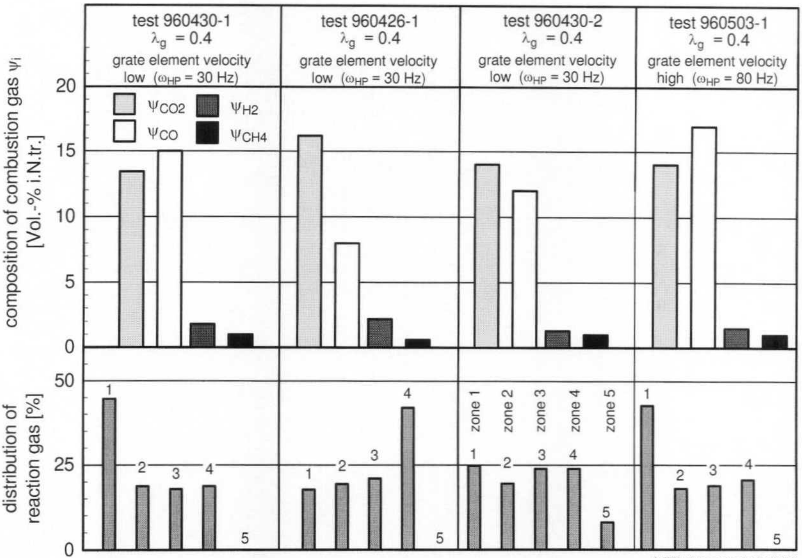

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Figure 4. Comparison of the composition of combustion gas with varying distribution of reaction gas along the grate path and grate element velocity.

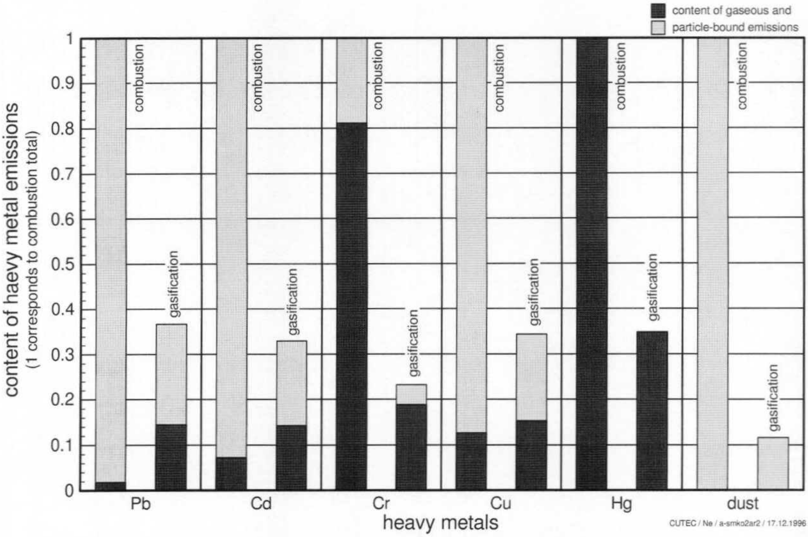

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Figure 5. Content of particle-bound and gaseous heavy metal emissions from the grate under gasification and incineration conditions.

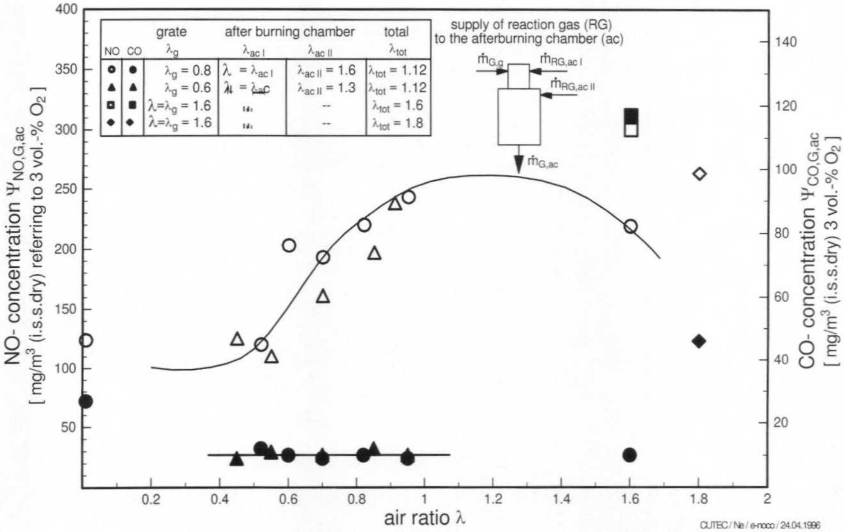

Figure 6. NO- and CO-concentration versus air ratio λ for combustion ($\lambda_g > 1$) and gasification ($\lambda_g < 1$) in the stoker system.