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3.3 Conventional Thermal Treatment Methods

3.3.1 Overview of Existing Thermal Processes

3.3.1.1 Introduction

Various processes which integrate pyrolysis, gasification and combustion fundamental structural units are currently being applied and tested in the field of the thermal treatment of municipal waste and similar industrial waste. The main thermal processes can be broken down into a

- first unit for the conversion of the solid and pasty waste and a
- second unit for the treatment of the gas, flue dust or pyrolysis coke produced in the first unit (Fig. 1).

	Unit 1	**Unit 2**	**processes and examples**
A.	combustion[1)]	combustion	combustion - post-combustion-process (e.g. standard waste incineration) [2] to [9], [16]
B.	thermolysis[2)]	combustion	thermolysis - post-combustion-process (e.g. Schwel-Brenn-Verfahren by Siemens KWU) [11]
C.	gasification[3)]	combustion	gasification - post-combustion-process (advanced standard waste incineration) [10], [12]
D.	thermolysis	gasification	thermolysis - post-gasification-process (e.g. Konversionsverfahren by NOELL [13], Thermoselect-Verfahren [14] etc.)
E.	gasification	gasification	gasification - post-gasification-process (e.g. gasification and gas decomposition by LURGI [15])

1) here: includes the processes drying, degasification, gasification and combustion

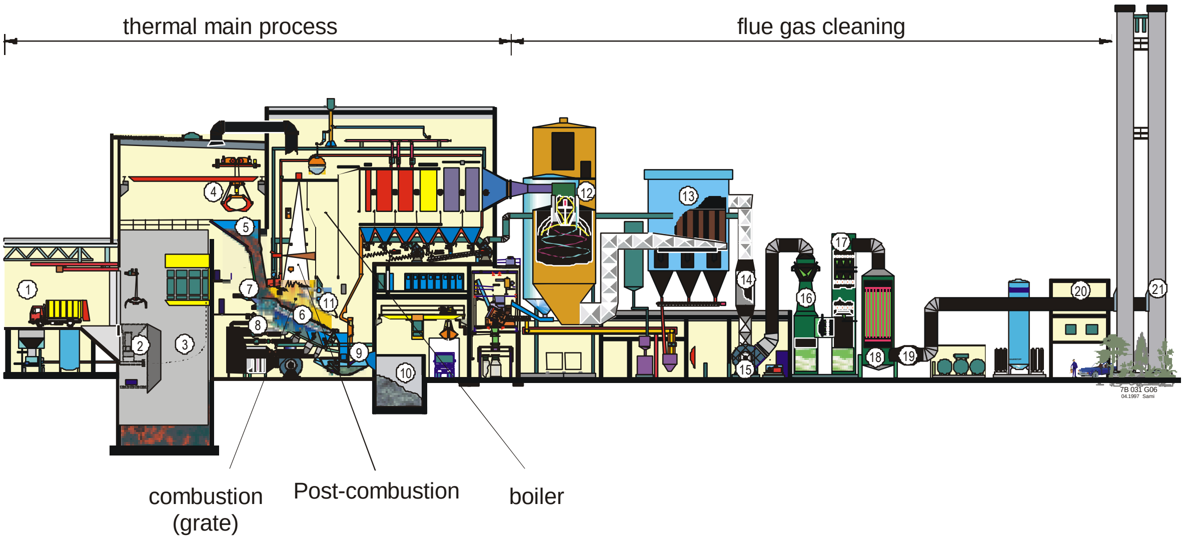
2) here: includes the processes drying, degasification and pyrolysis

3) here: includes the processes drying, degasification and gasification

Fig. 1. Systematic description of main thermal processes [1].

The conventional thermal treatment of residual waste, also often called „classical combustion of residual waste“, represents a tried and true technology. The systematic classification of processes is necessary in order to improve the discussion and optimization of processing technological possibilities and to enable a comparison of the processes in the first place. First, the processes for thermal waste treatment can be classified into the so-called main thermal processes and processes or plants for flue gas purification, energy conversion, ash treatment, production of supplementary agents, etc. The classical waste combustion can be viewed as a combustion-post-combustion process with a grate system in the first unit and a combustion chamber system in the second unit. According to the classification in Fig. 1 the Fig. 2 shows the profile of a complete process as an example.

The flue gas purification (so-called secondary measures) of the „classical“ process in particular has been improved in the last years. Plants equipped with state-of-the-art technology meet the statutory specified limits for the emission or dumping of pollutants into the air, water and soil.



technical data
pro unit:

waste input = 10,0 Mg/h
lower calorific value = 7610 kJ/kg
produced steam = 24,8 Mg/h
steam pressure (boiler) = 54 bar
steam pressure (superheator) = 40 bar
superheated steam temp. = 400 °C
feed-water temperature = 130 °C

legend

1 delivery
2 bulky refuse crusher
3 waste bunker
4 grab crane
5 charging hopper
6 reverse acting grate
7 charging equipment
8 primary air
9 ash discharge (wet)
10 ash bunker
11 secondary air
12 spray absorber
13 fabric filter
14 sound absorber
15 induced draught - blower
16 Venturi - scrubber
17 radial flow - scrubber
18 wet - electric filter
19 clean gas reheating
20 analytical room (emission measurement)
21 chimney

Fig. 2. Schematic representation of a waste power plant (classical household waste combustion plant) [2].

The current priority is the development, modeling and optimization of the process control (so-called primary measures) of the main thermal process. A considerable potential for development is present in the area of the grate and post-combustion in order to, for example,

- reduce the flue gas flow (flue gas purification plants, emission loads),
- improve the energy utilization and
- influence the characteristics of the residual material.

Considerable progress, triggered through the „new“ processes, have been made in the development with regard to the „classical“ processes with grate systems. The optimization of the design of the combustion chamber ([2], [3], [7], [16]), flue gas recirculation ([4], [5]), enrichment of the primary air with oxygen [6], water-cooled grate elements [7], further development of the control (e.g. IR-camera, [8], [9]), etc. should be mentioned as examples.

In addition, new, altered process control with grate systems such as e.g.

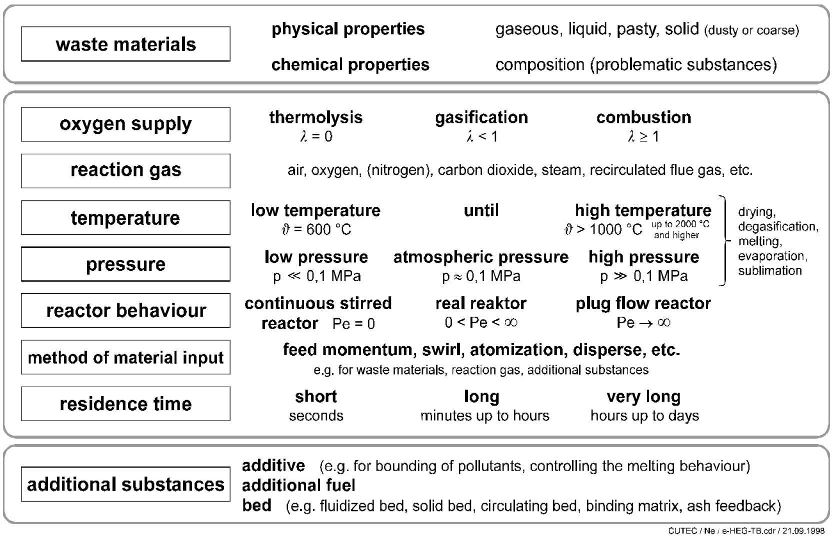
- the gasification with air on the grate and the therewith connected
- independent post-combustion of the gases produced

is being tested on the pilot plant scale for future developments [10] and recently also in small industrial scale [43]. The desired improvements toward the above-mentioned objectives are then even more pronounced.

In the following section, the general points of the process control in grate systems will be illustrated briefly. Then examples of process control in plants implemented practically and results of experiments in industrial and pilot plants as well as on the laboratory-scale will be discussed.

3.3.1.2 Process control in grate systems

The efficiency of the thermal process for the treatment of waste is primarily determined through the process control of the main thermal process. The possibilities available for the reduction of pollutants and flue gas flows through primary measures must be exhausted. The expenditure necessary in the range of secondary measures, e.g. the flue gas purification, is then adjusted accordingly. Based on this, we will focus on the thermal treatment of the classical waste combustion which can, as mentioned at the beginning, be divided into two units according to the combustion-post-combustion concept. Combustion on the grate takes place in the first unit. Then, the gases and flue dust arising from the grate are combusted in the post-combustion chamber in the second unit. Due to the different tasks of the first and second units, the steps of solid conversion on the grate (first unit) and post-combustion of the gases (second unit) will from now on be treated separately.



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 temperature** $\vartheta = 600$ °C	**until**	**high temperature** $\vartheta > 1000$ °C up to 2000 °C and higher	drying, degasification, melting, evaporation, sublimation
pressure	**low pressure** $p \ll 0{,}1$ MPa	**atmospheric pressure** $p \approx 0{,}1$ MPa	**high pressure** $p \gg 0{,}1$ MPa	
reactor behaviour	**continuous stirred reactor** $Pe = 0$	**real reaktor** $0 < Pe < \infty$	**plug flow reactor** $Pe \rightarrow \infty$	
method of material input	**feed momentum, swirl, atomization, disperse, etc.** e.g. for waste materials, reaction gas, additional substances			
residence time	**short** seconds	**long** minutes up to hours	**very long** hours up to days	
additional substances	**additive** (e.g. for bounding of pollutants, controlling the melting behaviour) **additional fuel** **bed** (e.g. fluidized bed, solid bed, circulating bed, binding matrix, ash feedback)			

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Fig. 3. Main influential parameter [1].

Each reaction condition is determined through the main influencing parameters (Fig. 3). When discussing the partial steps of the solid conversion and the combustion of the gases generated, the main influencing parameters mentioned in Fig. 3 (e.g. [1]) must be considered with respect to the level and control possibilities through plant technology (apparatus technology). This of particular value when regarding the individual reaction mechanisms (e.g. formation and degradation of pollutants). The various control possibilities along the reaction pathway are of particular importance for the optimization of the process.

Solid conversion in grate systems

The solid conversion on a grate can more or less be divided into the following partial processes in the direction of the reaction pathway (Fig. 4):

- drying,
- degassing,
- gasification and
- residue burn out.

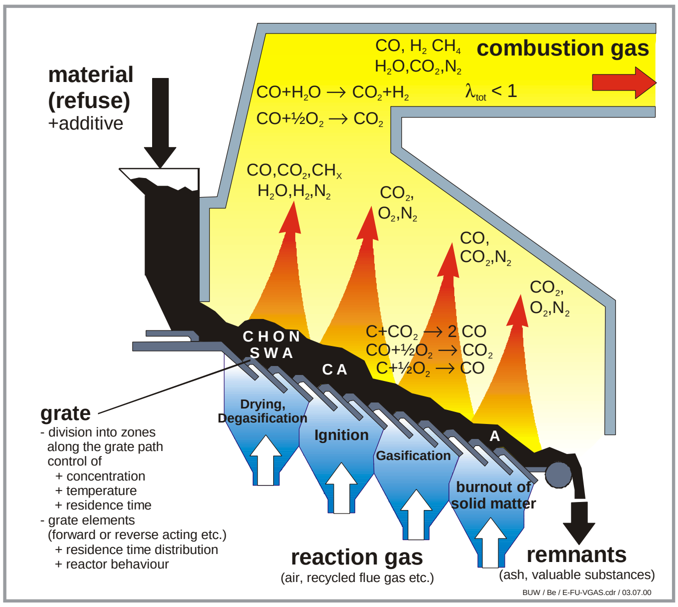

Fig. 4. Schematic representation of the solid conversion in grate systems during the combustion process.

Since the oxygen supplied to the reaction gas of the grate (usually air) relative to the waste added leads to overstoichiometric conditions (e.g. $\lambda \approx 1.3$), it can be considered as „combustion on the grate“.

In order to be able to discuss process-engineering possibilities, the main influencing parameters must be regarded [1]. Not only the actual level but also the distribution of the main influencing parameters along the reaction pathway must be considered. There are many different possibilities for the control of the above-mentioned main influencing parameters in grate systems which can selectively influence individual partial processes along the reaction pathway (Fig. 5). These control possibilities are particularly advantageous when dealing with variations in the reaction behavior due to fluctuating composition of the waste. The following representations of the process-engineering possibilities are also depicted in the overview Fig. 5 and the flowchart in Fig. 6.[1]

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[1] In this case, the main focus is on the process control for solid input material in grate systems. When considering the process control possibilities, the incineration of gaseous, liquid and dust-like feed material must first be discussed since generally only one unit is necessary for these. Then, using this

It should be mentioned beforehand that the quench reactions at the surface of the wall should be avoided and therefore a corresponding high wall temperature through suitable refractory lining should be guaranteed for both units (grate and post-combustion). This also means that the heat transfer must be carried out separately from the solid conversion and the post-combustion as far as possible, i.e. combustion and heat decoupling are to be connected in series as shown in Fig. 6. It can also be seen in Fig. 6 that the two combustion units are drawn in series and separate.

Starting materials	
	Lumpy, also pasty when in connection with a solid or inert bed
Amount of oxygen available	
Level	Usually overstoichiometric (combustion), understoichiometric (gasification) possible; making independent post-combustion possible; oxygen exclusion (pyrolysis) not customary
Control along the reaction pathway	Very well adjustable (e.g. air/oxygen gradation, flue gas recirculation, etc.) when separated into individual zones; the partial steps of drying, degassing, burn out of the solid can be influenced in connection with temperature control
Temperature	
Level	Bed surface temperature up to ca. 1000 °C and higher; average bed temperature lower
Control along the reaction pathway	Very good possibilities through separation into several zones as with the control of the oxygen concentration (preheating of the air, flue gas recirculation, water/vapor cooling)
Pressure	
	At standard pressure, generally only a few Pascals underpressure due to the plant construction
Reactor behavior	
Solid	According to the movement of the grate elements, the individual zones can approach continuously stirred reactor characteristic (e.g. reverse-acting grate) of a plug flow reactor characteristic (e.g. travelling grate); over the entire reactor length, a plug flow reactor characteristic results
Gas	a) Oxidizing agent etc. is forced to flow through the bed and is distributed evenly over the bed surface, resulting in very good contact between gas and solid b) Flow control over the bed possible as counter and parallel flow, gas treatment in the following process step necessary (e.g. post-combustion)
Residence time	
Level (average residence time)	In the range of several minutes to hours; adjustable through grate speed and mass flow and can be influenced in the project design through total length and width
Control along the reaction pathway	Very good adaptation possible through separate speed regulation of the grate elements in the individual zones; control through discharge roller if necessary for additional improvement of the burn out at the end of the grate
Additives	
	Additives for the binding of pollutants in the solid and influence of the characteristics of the residue (ash, partly fused ash, slag); inert bed e.g. matrix for possible easily melted substances (e.g. plastic)
Functional range (examples)	
	For the solid conversion in the first step in household waste combustion plants; separation of metals from the composite at low temperatures and simultaneous understoichiometric conditions

Fig. 5. Characterization of grate systems [44].

This should make it clear that the different partial steps

- solid conversion on the grate and
- post-combustion process

can be optimized more easily, the more decoupled the two units are. In order to achieve this, not only a geometric separation is possible, but also, as will be explained in connection with the post-combustion process, a fluid dynamic decoupling.

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information as a basis, one can shift to the process control for lumpy and pasty materials which generally require two units. Since the systematic representation would take up too much space, the procedure and references are mentioned here (e.g. [1], [4], [45]).

The division of the grate area into several grate zones which are separate from one another with respect to the reaction gas supply must also be mentioned when evaluating the control possibilities of grate systems. This makes it possible to control the amount of oxygen available and the temperature in the bed along the reaction pathway through variation of the supply of reaction gas so that the individual steps, ending with burn out of the residue, can be matched to suit the characteristics of the starting material, even with fluctuating composition.

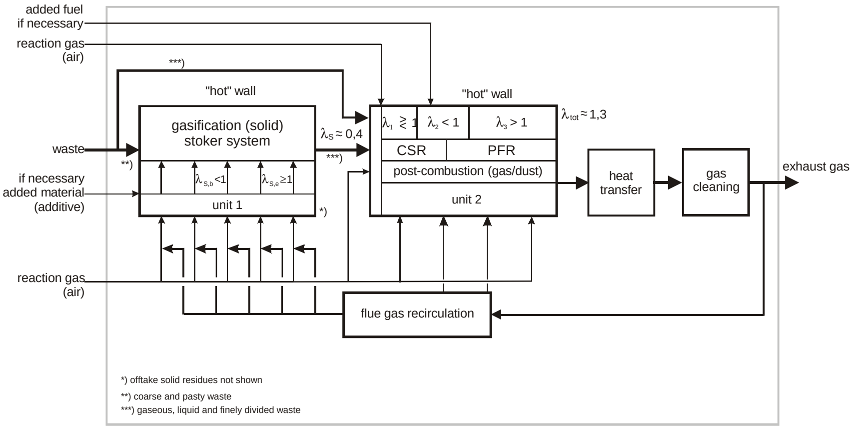


Fig. 6. Schematic representation of the separated process control; combustion/gasification-post-combustion process with grate and combustion chamber system [4], [45].

An additional leeway with regard to distribution of oxygen and temperature is achieved when inert gas, recycled flue gas or additional oxygen is given as reaction gas to certain waste materials instead of air (downdraft). A preheating of the reaction gas can also be considered for waste materials with low heating values.

Through the variation of the distribution, the oxygen content and the temperature of the reaction gas, the burn out of residues from waste with varying heating values and mass flows in particular can be optimized on the one hand. On the other hand, the temperatures and residence times in the combustion chamber can be influenced directly over the bed with respect to the post-combustion process.

When considering the control of the gas flow over the bed, one can differentiate between parallel, center or counter flow principles. In the parallel flow principle, a first post-combustion of the gases emitted from the beginning of the grate occurs. In the counter flow principle, the hot gases from the end of the grate in the drying and degassing zone should convey heat to the beginning of the grate. The gases, flowing parallel or counter, can be post-combusted optimally independent of their condition at the post-combustion chamber if the separated process control of the grate (1st unit) and the post-combustion process (2nd unit) is available. This makes it possible to implement common primary measures for the reduction of NO_X with a simultaneous high burn out. Similarly, the temperature conditions in the drying and degassing stages are not only dependent upon the flow control. The heat transfer ratios can be influenced through the so-called secondary heating surface effect, i.e. though radiation exchange between the surrounding refractory-lined hot walls and the surface of the material. These things are considered in order to guarantee that no certain flow control is preferential from the start.

An additional degree of freedom in the optimization of the course of combustion (according to the residence time and residence time behavior) is gained through the separation of the movement of the grate elements into zones. The separated movement of the grate elements into the grate zones along the path of the grate means, on the one hand, an increased construction expenditure but on the other hand, the residence time and bed height can be controlled independently in the individual reaction zones. The grate itself can be used as forward-acting, reverse-acting or roller grate.

Through an additional water-cooling of the grate elements, which makes the construction more complex than the conventional grate, the reaction gas distribution, oxygen concentration and temperature can be varied over a wider range regardless of the grate construction (cooling) in contrast to the grate cooled only with reaction gas (air). The above-mentioned measures and accompanying advantages can be transferred even more distinctly. The excess-air coefficient, the flue gas and flue dust flows can be reduced. The temperature in the burn out stage can be increased to the point that the ash accumulates in a sintered state, which leads to a marked improvement of the elution behavior of the residual waste [14], [36]. Furthermore, the water-cooled grate results in a lower risk of wear through thermal influences for waste materials with high heating values and a low ash sifting through the grate in particular (low thermal expansion permits little clearance between the grate elements).

The control of the combustion process on the grate through the use of an infrared camera (IR camera) for the detection of the temperature at the bed surface was also mentioned. The position of the main reaction zone can be identified through the measurement of temperature fields. This zone can be shifted toward the beginning or end of the grate e.g. through the redistribution of the primary air. Through selective change of the primary air (reaction gas input), a fast adjustment to fluctuations in the waste composition, an avoidance of gas blow through and streaming, an improvement of the residue burn out and the avoidance of emission peaks can be expected.

Post-combustion process

In connection with the post-combustion process, the main influencing parameters (Fig. 3) and corresponding control possibilities should be discussed in the same way as before for the solid conversion process. An overview is shown in Fig. 7.

First, the residence time in connection with the formation and decomposition reactions of pollutants is considered. In chemical process-engineering one differentiates between two limiting cases with regard to the residence time behavior: the ideal continuously stirred reactor (CSR) and the plug flow reactor (PFR) [20]. Fig. 8 shows the decomposition of CO dependent upon the residence time for these two reactor characteristics. It can be seen that the plug flow reactor exhibits the best reactor characteristics for the decomposition. It is thereby assumed that the temperature and concentration profiles are constant through the cross-section of the reactor cross-section. For the conditions in the post-combustion process, this means that stirred reactors must be connected to ensure mixing (Fig. 6, second unit, first stage).

Starting materials	
	Gaseous, liquid, dust-like
Amount of oxygen available	
Level	Overstoichiometric to understoichiometric; variable over wide ranges; if overstoichiometric at reactor discharge: called “combustion chamber”; if understoichiometric at the end: called “gasification reactor”
Control along the reaction pathway	Very good through gradation of oxidizing agent and fuel along the reaction pathway (introduced over stirred reactor elements)
Temperature	
Level	Different combustion temperatures in the range from 1000 °C to 2000 °C or more; range is very variable
Control along the reaction pathway	In addition to the staging of oxidizing agent and fuel along the reaction pathway, intervention through flue gas recirculation, spraying of water etc. possible; indirect heat coupling and decoupling through corresponding heating or cooling systems; many possibilities
Pressure	
	At standard pressure, generally only a few Pascals underpressure due to the plant construction; high-pressure combustion rare; pressure gasification more common
Reactor behavior	
Dust/gas	Hydraulically, stirred reactor as well as plug flow characteristics can be approached for dust and gas
Residence time	
Level (average residence time)	In the range of seconds (longer at higher pressure); adjustable through load conditions and can be influenced in the project design through geometric dimensions
Control along the reaction pathway	Very difficult; residence time distribution can be controlled over the reactor behavior
Additives	
	Additives, in particular, introduced over the stirred reactor elements, fin order to bind pollutants (e.g. sulfur dioxide, nitroxides) as well as to influence the slag characteristics and melting points of the dust
Functional range (examples)	
	Combustion of liquid residues; post-combustion of gas and dusts in the second step of the thermal treatment process; high temperature gasification of residues for the production of process gas (low and high temperatures); certain combustion processes (e.g. recirculation of chlorine as hydrochloric acid in the production cycle etc.)

Fig. 7. Characterization of combustion chamber systems [44].

It should again be mentioned here that an amplified heat decoupling combined with a quench effect at a cold wall is to be avoided in order to guarantee a uniform temperature profile. Mechanical components can generally not be applied for mixing due to the high temperature, corrosion, etc. Two fluid dynamic stirring mechanisms can be used:

- so-called supercritical swirl flow with linear recirculation or recirculation of hot gases ([22], [23]) for plants with low capacity or

- single or multiple jets arranged above or next to each other which act as injectors to draw in and mix the surrounding ([4], [24]).

The installation of such an intense mixing zone (stirred reactor element) at the entrance of the post-combustion leads to the above-mentioned hydraulic separation as represented in Fig. 6. This is supported when the mixing zone is arranged in a narrowed cross-section. A relaxation zone (plug flow reactor as suitable reactor characteristic for the decomposition) is situated above the mixing zone.

A high intensity in the mixing zone must be achieved in order to guarantee the greatest possible burn out (CO, hydrocarbons, flue dust). Plants with greater capacities are generally equipped with injector jets. A good cross-sectional overlap, a sufficient injector jet penetration depth and an adequate suction of the residual current (flue gas flow from the grate) must be achieved through the proper layout of the jet geometry, the number and arrangement of the jets as well as the inlet impulse.

Measures for the control of the amount of oxygen available along the reaction pathway are, for example:

- air staging,
- fuel staging,
- flue gas recirculation,
- oxygen supply
- etc.

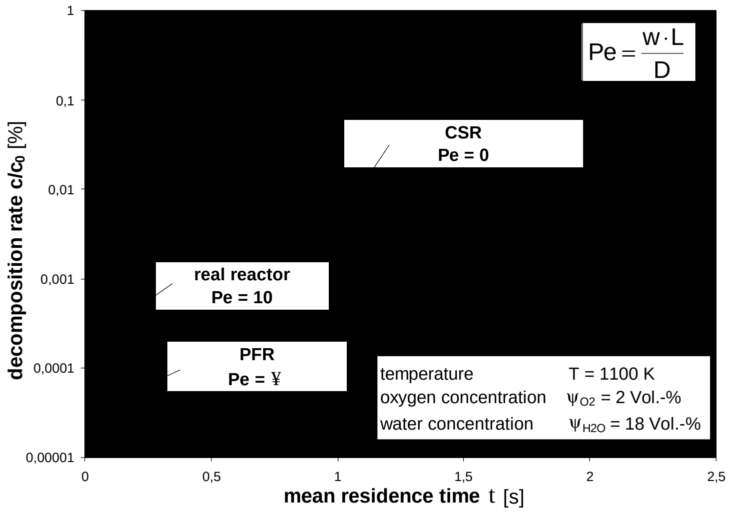


Fig. 8. Dependence of the CO decomposition on the average residence time and the mixing conditions in the reactor [1], [21].

When considering the control of the above-mentioned main influencing parameters, sufficient possibilities are available to optimize the process control with respect to the mechanisms of formation and decomposition of pollutants. At this point, the extensive experience and knowledge concerning the reduction of nitroxides and the improvement of the burn out of gaseous, liquid and dust-like fuels in particular should be mentioned. This experience should be transferred to the post-combustion.

3.3.1.3 Examples and Results

The explanations concerning the main influencing parameters and the principle control possibilities through the process control make the discussion of already existing plant concepts possible while simultaneously making the potential for development clear. The discussion of the individual aspects of the process control without reference to the main influencing parameters, for example in the form of questions if counter or parallel flow, forward-acting or reverse-acting grate are more suitable for waste combustion, appears to be inappropriate due to the complexity of the processes. It should be mentioned that e.g. plant conceptions with a forward-acting grate and those with a reverse-acting grate can both achieve good practical results. The following discussion of the effect of certain process controls is important to understand the processes taking place during waste combustion. However, no estimation of the total concept of the plant can be derived from the evaluation of the individual aspects.

The solid conversion on the grate will be covered in the first section and then the post-combustion process.

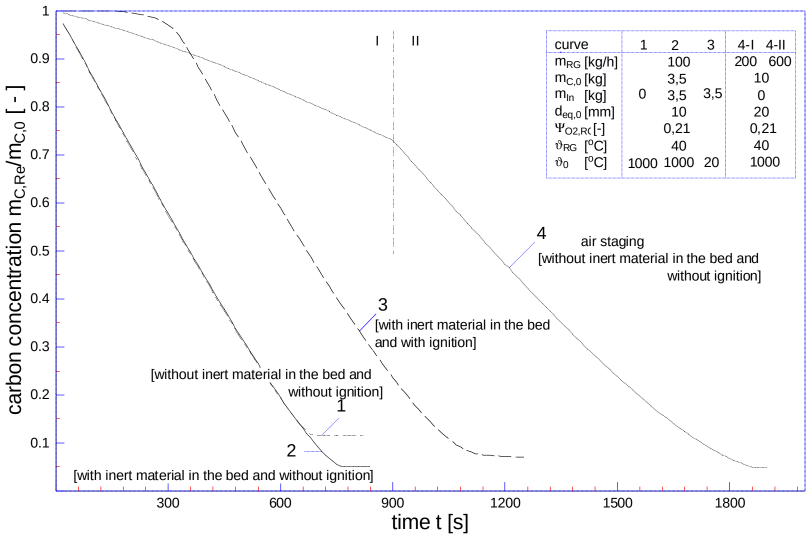
Solid conversion on the grate

The main goals of the solid conversion on the grate are the utilization of the ash in a high burn out (low residual carbon content) and a small as possible (available) concentration of heavy metals and salts.

These objectives are influenced, aside from the composition of the waste, mainly through the main influencing parameters temperature, oxygen concentration and residence time as well as residence time behavior or mixing behavior. A circulation of „ignition cores“ ([8], [46]) and a stabilization of the temperature in the bed is achieved through the intensive mixing of the bed in the reverse-acting grate system with respect to the ignition of the bed in particular. Due to the early ignition of the bed in reverse-acting grate systems, the addition of primary air generally already reaches its maximum in the second primary air zone. The maximal temperature in the bed is also reached in this section. Reverse-acting grates can be approximated in the individual sections as stirred reactor elements with respect to the residence time behavior ([32], [47]). A forward-acting grate system can be considered as a plug-flow reactor with reference to the mixing behavior. The input of the primary air into the drying and ignition phase must be regulated carefully in order to avoid a break in the ignition front. The main air is generally added in the middle of the grate. The primary air in the burn out zone must be adjusted carefully for a high burn out regardless of the type of grate. A too high primary air current in the burn out zone can lead to a „blow cold“ (extinguish) of the bed and a corresponding high carbon content in the ash. The influence of the amount of inert material (ash) in the fuel on the burn-out will be considered more closely. The inert material acts as „heat reservoir“ which takes up heat corresponding to its capacity in the main combustion zone at high temperatures. Due to this heat reservoir, the threat of „blow cold“ in the burn-out zone is reduced. This positive influence of the inert material should be considered in connection with the demand of the separation of the inert material, e.g. through mechanical-biological processes aimed toward supplying less „ballast“ through the incineration process.

The influence of the air staging and the inert material on the burn-out can be clearly shown through calculations with the help of mathematical models for the solid conversion. Although the model cannot be discussed here in detail, it should be mentioned that the solid conversion of unknown fuels in grate systems can be described for stationary and changing practical processes using this model [18]. The residual carbon content with regard to the initial amount in the bed element over time for various boundary conditions is shown in Fig. 9 (see legend in Fig. 9). A comparison of curves 1 and 2 in Fig. 9 clearly show the influence of the inert material as described above. A significantly better carbon conversion is achieved with inert material than without. Curve 4 shows the influence of a air staging for a fuel without inert material in which the residual carbon content is as low as that for case 2 (without air staging).

To ensure an even distribution of primary air, the pressure loss in the grate element must be much higher than that in the waste bed, independent of the type of grate. If the main fluid resistance for the reaction gas (downdraft) is located in the grate element, then an even distribution of waste over the grate surface results regardless of the accumulation of the grate element with waste (fuel bed).



curve	1	2	3	4-I	4-II
m_{RG} [kg/h]		100		200	600
$m_{C,0}$ [kg]		3,5		10	
m_{In} [kg]	0	3,5	3,5	0	
$d_{eq,0}$ [mm]		10		20	
$\Psi_{O2,RG}$ [-]		0,21		0,21	
ϑ_{RG} [°C]		40		40	
ϑ_0 [°C]	1000	1000	20	1000	

Fig. 9. Calculated carbon concentration vs period of time for a given bed [18].

Different specifications, with respect to the different residence time behaviors of beds on forward-acting and reverse-acting grate systems, also exist for the control of the residence time along the grate pathway. For forward-acting grate systems, a control of the grate speed in several grate zones independent of one another is generally possible. However, for reverse-acting grate systems, such a differentiated control of the residence time is not carried out. A so-called discharge drum for the additional control of the residence time in the burn out zone is found more often in reverse-acting than forward-acting grates [46].

The course of combustion is influenced, in addition to the distribution of the primary air, through the temperature and oxygen concentration of the primary air (reaction gas). The primary air is generally preheated to temperatures of $\vartheta = 140$ °C, which is particularly advantageous for the drying and burn-out phase. Higher bed temperatures are also reached in the main combustion zone through a preheating of the air. The increase of the oxygen concentration to up to 35 vol.-% in the reaction gas is carried out e.g. using the “SYNCOM Process” [6]. This guarantees the burn-out and the criteria for the landfill class I [48] and causes a reduction in the flue gas flow (see below). In addition, the gas flowing through the bed can be reduced which leads to a decrease in the amount of flue dust and the diameter of the flue dust particles.

The temperature along the grate pathway is still influenced by the control of the gas flow over the bed. In the parallel flow principle, a combustion of the gases coming from the beginning of the grate is sought. The hot gases are then lead over the burn out zone. On the other hand, in the counter flow principle, the hot gases should transfer heat from the grate end in the drying and degassing zone to the beginning of the grate. The flow control will be discussed later with regard to the post-combustion. At this point it should be mentioned that the temperature level in the drying and burn-out phases is influenced through the design of the combustion chamber geometry (secondary radiation surface). This so-called secondary heating surface is of more importance in the burn-out zone of a counter flow combustion than a parallel flow combustion. In the parallel flow combustion, the design of the combustion chamber must avoid slagging - for wastes with high heating values in particular.

The use of water-cooled grate elements leads to the above-mentioned advantage that the primary air distribution is less dependent upon the cooling of the grate elements. This can then result in further improvements with respect to the ash quality (increase in temperature and reduction of the oxygen concentration) in experiments on the pilot plant scale ([19], [36], [37]). In addition, the flue dust concentration (see above) is reduced through the lowering of the primary air. The water cooling also has the advantage [7] that the wear through thermal influences is reduced and that, even at high heating values, there is no threat of thermal overload and that the grate siftings are decreased (less expansion allows for narrower slits between the grate elements).

The setting of the primary air supply, grate speed, waste feed, etc. is carried out using firing power control in order to ensure an even course of combustion and highest possible burn out [2]. The firing power control can be supported through additional detectors and measuring signals, e.g. IR camera [8], pyro-detectors [9], „heating value sensors“ [49].

Whereas the setting of the process control for a high burn-out is state-of-the-art in the practice, the optimization of the process parameters with respect to the selective release or binding of heavy metals in the ash (primary measures for the improvement of the ash quality) is still a current research topic. Approximately 300 kg/Mg$_{\text{waste}}$ grate ash remain after the waste combustion, from which ca. 40 kg/Mg$_{\text{waste}}$ scrap iron can be separated. Currently, ca. 3 million Mg/a grate ash accumulate in Germany, of which ca. 50 % to 60 % are used as secondary building material in road and path construction and the rest is deposited in overground landfills [50]. The aim of future developments must be the improvement of the ash quality through primary measures in order to make a high-grade utilization possible.

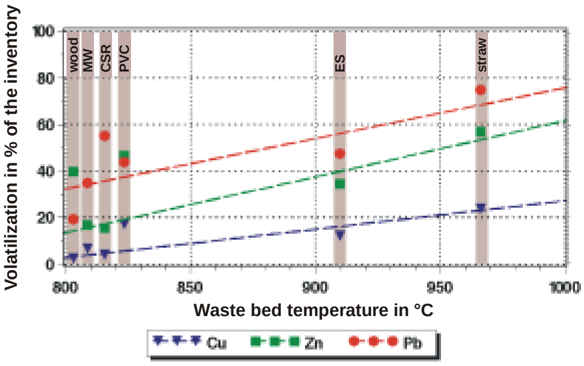


Fig. 10. *Relationship between volatilization and waste bed temperature [36].*

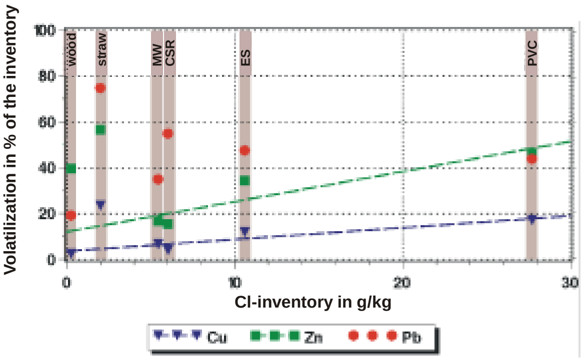


Fig. 11. *Relationship between volatilization and Cl inventory [36].*

Dependent upon the combustion conditions, heavy metals, chlorine, sulfur and fluorine etc. are released from the fuel bed and bound by the ash. One can differentiate between highly volatile substances such as Hg, Cd, As, Cl middle volatile substances such as Pb, Zn, S and nonvolatile substances such as Cu.

Investigations with various waste compositions in a pilot plant have shown that the evaporation of heavy metals (e.g. Cu, Zn and Pb) is correlated with the bed temperature and chlorine content (Fig. 10, Fig. 11; MW = municipal solid waste, reference fuel; CSR = car shredder residue - light-weight fraction; ES = plastic scrap from electronics) [36].

An additional parameter for the evaporation is the oxygen concentration. Results from experiments with radioactive tracers (^{69m}Zn) in a pilot plant [37] clearly show the different behavior for the release of zinc under reducing and oxidizing conditions. The measured zinc evaporation for three different operation conditions is shown in Fig. 12. The two parameters which were varied on the grate were the oxygen partial pressure and temperature. The redox conditions of the incineration process were changed from combustion to gasification operation by decreasing the flow rate of primary air to one third. But even in the so-called combustion operation mode, reducing conditions dominate in the solid bed in the first primary air zone. The temperature variation was achieved by adjusting the water content in the waste material. Fig. 12 reveals that the trend of zinc evaporation is independent of the operating conditions and the amount of evaporated zinc. The evaporation takes place very fast i.e. in a narrow area on the grate. However the location of the evaporation depends on the operating conditions. The evaporation always occurs at locations with high temperatures and with reducing conditions and can reach up to 100 % evaporation. For the experiment in which only 50 % evaporation of the radio tracer was obtained (wet, oxidizing), one could expect the following: First, the location of evaporation is shifted to places further down the grate, due to a delayed in reaching the necessary temperature. Second, the shift in the temperature profile brings the evaporation zone for zinc into the region where oxidizing conditions prevail (air zone 2). More and more zinc oxide is produced which is not volatile and therefore further zinc evaporation is stopped. The possibility that a thermal mobilization of heavy metals at high temperatures is supported by the reducing effect of the hot carbon in the fuel bed is referred to in [36].

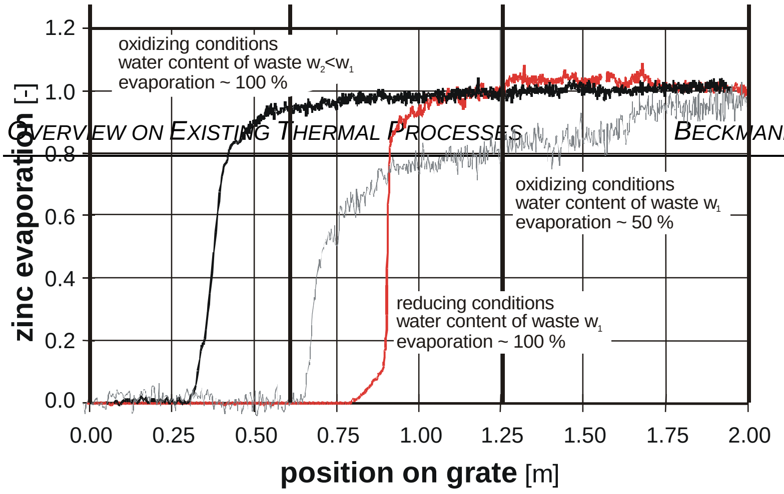


Fig. 12. Normalized Zn amount detected in flue gas scrubber after the pulsed addition of Zn tracer at position 0. Accumulation is monitored while tracer is transported along the grate (0.0 m to 2.0 m). oxi.: oxidizing conditions; red.: reducing conditions (gasification); w: water content of waste; evaporation: % of tracer transferred to flue gas [37].

It should also be mentioned in connection with the ash quality that a marked decrease in the extractability of pollutants can be achieved through a sintered state in comparison with the so-called dry state. Through the transition from the sintered to the melted state, only relatively small improvements with respect to the extractability are achieved [36].

Post-combustion

The main objective of the post-combustion process is primarily the degradation of CO and organic trace elements as well as the burn-out of fly dust (a total high burn-out). The minimization of NO through primary measures is also being investigated for direct practical implementation. The process control of NO minimization with simultaneous high burn-out in connection with the firing systems for gaseous, liquid and dust-like fuels is already state-of-the-art ([25] to [29]).

The main influencing parameters to achieve this objective are temperature, oxygen concentration, residence time and residence time behavior. These parameters are determined through a series of individual aspects of the process control and not only through the flow form which is often discussed in connection with an initial post-combustion of the gases (e.g. parallel flow) or the minimization of NO in the combustion chamber above the bed. Through an appropriate separation of the post-combustion zone (2nd unit) from the grate zone (1st unit), the gases, flowing parallel or counter, can be post-combusted optimally regardless of their state at the entrance to the post-combustion. The separation of the post-combustion from the grate as shown in Fig. 1 will be discussed in more detail in [1]. The separation does not have to be geometric, it can also ensue hydraulically. A geometrical separation would however be optimal (for example over a tube).

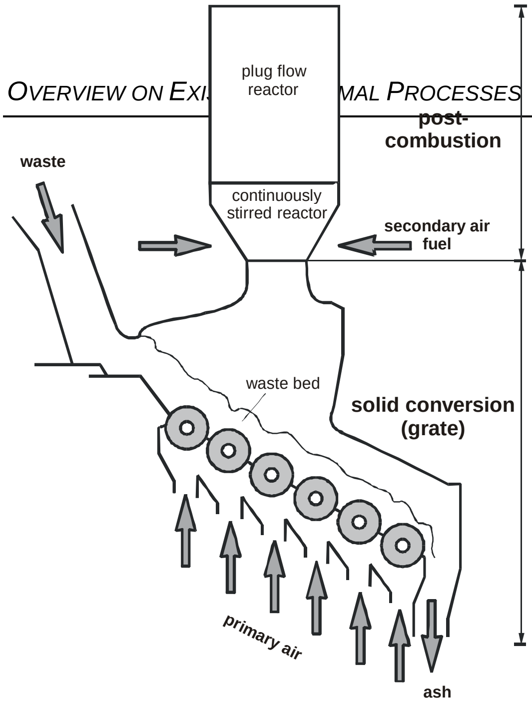


Fig. 13. Schematic representation of the grate and post-combustion zone [51].

This can however generally not be carried out for practical reasons. A hydraulic separation (Fig. 13, Fig. 14) is also very effective when, for example, a good „overlap of the cross-section“, adequate suction of the residual current to be mixed and sufficient „penetrating depth“ of the injector jets is achieved according to the jet depth theory through dimensioning of the jet geometry and penetration impulse. This generally leads to fields of jets in several levels (Fig. 15). If possible, fields of jets should be arranged on all channel sides to ensure good overlap. The positioning of the injection along a narrowed cross-section in the post-combustion zone supports the mixing (Fig. 14, Fig. 15). This hydraulic separation also leads to the formation of the continuously stirred reactor element (CSR) shown in Fig. 6. The settling section is then located above the fields of jets (Fig. 14, Fig. 15) („plug flow zone"). The average velocity w_x of an injector stream which penetrates the combustion chamber above the secondary air jets with a speed of w_0 decreases approximately hyperbolically with the penetration depth of the stream x. In the combustion chamber, the stream is diverted in the direction of the upstreaming gas y, depending on the ratio of the flow rate of the upstreaming gases w_y to the exit velocity of the stream at the jet w_0 proportional to the square of the penetration depth x^2. Through the reduction of the velocity w_x and the diversion of the stream Δy, the mixing is worsened correspondingly. The installation of a so-called prism in the combustion chamber has served to improve the mixing conditions both for old and new plants with large cross-sections in the area of the secondary air injection and the corresponding large penetration depths in particular (Fig. 16). In this system, first installed in the MSW-Incineration plant in Bonn, the flue gas from the grate is divided into two partial flows “A” and “B” by a membrane-wall construction in the shape of a prism. The prism is

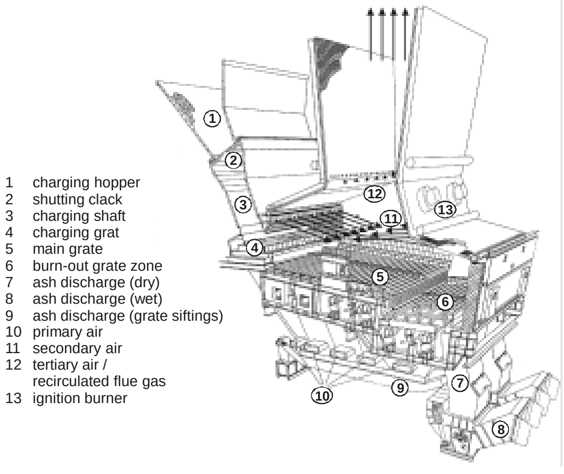


Fig. 14. Schematic representation of the forward acting grate and separated post-combustion zone [7] .

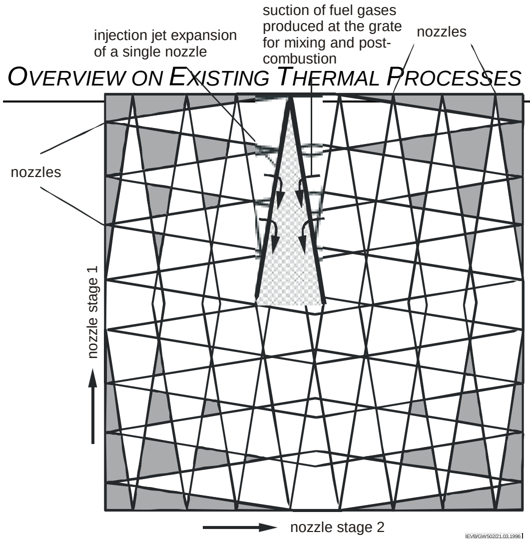


Fig. 15. Possible arrangement of fields of jets in two levels for the formation of a „stirred reactor element“ [4].

water-cooled and protected with refractioning material. Secondary air is injected into the divided flue gas streams “A” and “B” as indicated in Fig. 16, reducing the jet length over the cross-section correspondingly. Through the installation of the prism, a much shorter and clearly defined burn-out of the flue gases just above the prism could be achieved [16].

The injection of secondary air should be avoided as much as possible. The substitution of secondary air through recirculated flue gas reduces the flue gas mass flow (at the chimney) on the one hand and on the other hand prevents temperature peaks in the post-combustion through intense mixing when the injector jets are positioned properly. This leads to a decreased thermal formation of NO. The influence of the flue gas recirculation in the post-combustion process of a waste combustion plant is shown in Fig. 17 [5].

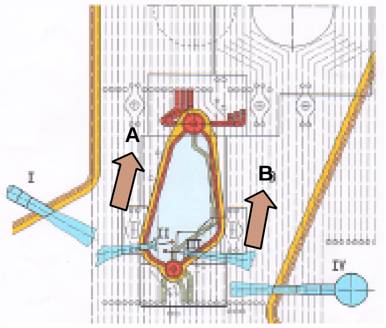


Fig. 16. Cross-section Prism [16].

The flue gas recirculation was simulated through the addition of nitrogen (inert gas). The mixing of the flue gas originating at the grate is carried out at a high inert gas ratio with injector jets which contain almost no oxygen. High temperature peaks can then be avoided. Altogether, a decrease in the NO_X concentration is achieved. The constant low CO concentration with regard to the inert gas ratio shows that the CO conversion is not directly dependent upon the oxygen available in this case for a correspondingly designed mixing capacity.

A different separation between grate and post-combustion as represented in Fig. 13 is shown in Fig. 18. Here, the stirred reactor element for the post-combustion of the gases emitted from the grate is situated above the first half of a drum grate. The post-combustion zone now only consists of the „calmed burn-out zone“ (plug flow reactor zone in Fig. 13).

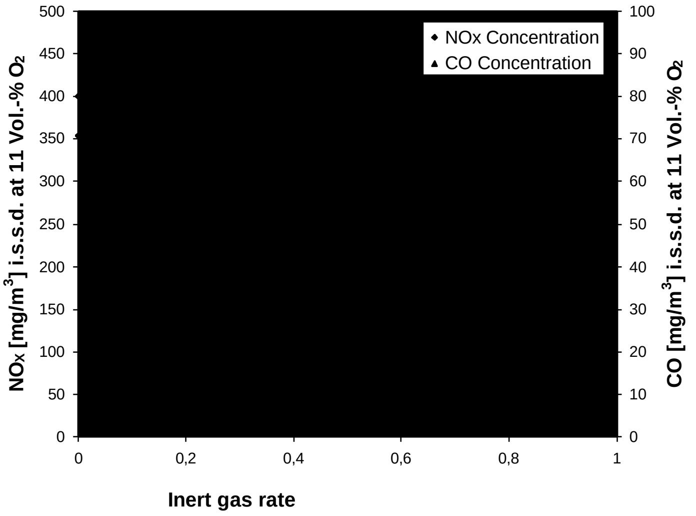


Fig. 17. NO and CO gas concentration dependent upon the inert gas rate [5].

The European Combustion Guidelines, based on the 17th BImSchV, set process-internal requirements for the minimum values of the oxygen concentration, temperature and residence time (6 vol.-% O_2, 850 °C, 2 s) with the objective of guaranteeing a sufficient burn-out. This requirement forces the operator to increase the temperature in the combustion chamber through e.g. the reduction of the primary excess-air coefficient. This intensification of the combustion requirements in connection with the increased heating values in recent years leads to higher thermal load and more corrosion and therefore to less availability of the plant [38]. In connection with the principle requirements for the post-combustion step (see above) as well as with the example discussed, it has become clear that the main influencing parameters oxygen concentration, temperature, residence time and reactor behavior (mixing) cannot be discussed individually, especially with respect to a high degradation of CO and organic trace elements. This relationship was confirmed in a practical plant (MHKW Mannheim) within the framework of a research project [39]. Five experiments were carried out in the waste reactor 2 of the HMVA Mannheim in which the parameters combustion air and amount of waste were varied in order to influence the oxygen concentration, temperature and residence time. The experimental settings were accompanied by an extensive measurement, sampling and analysis program for the flue gas flow (gas and dust) and the grate

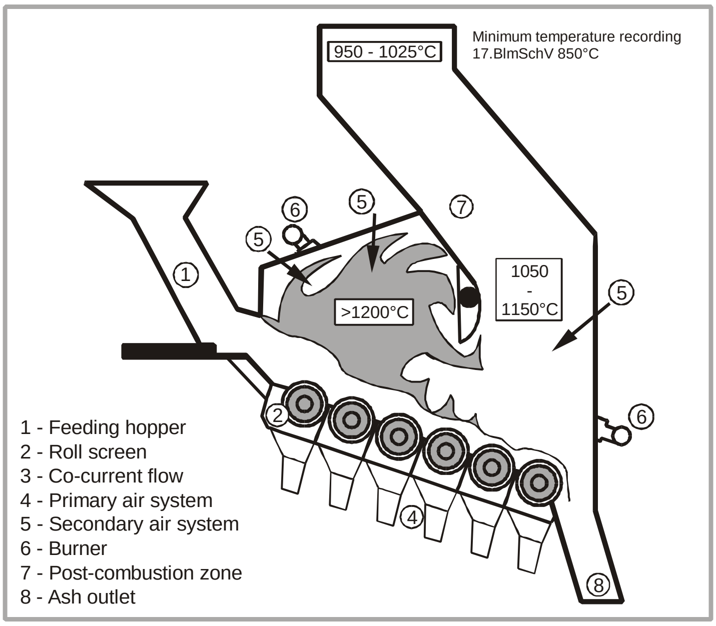


Fig. 18. Drum grate with „Feuerwalze“ [3].

ash. The residence time range for the flue gas during the experiments at temperatures above 850 °C was between $\tau_{850} = 0.7$ s and 2.27 s. An important result of the experiments is that no direct connection is evident between the pollutant concentration in the flue gas and the residence time in the post-combustion chamber. The influence of the mixing (reactor behavior) with respect to the results shown in Fig. 19 should also be mentioned here[2]. The experimental settings V5 (total load) and V2 (partial load) result in almost identical requirements concerning heating value, fire position, combustion chamber temperature and flue gas composition. They differ however in the load conditions with respect to the flue gas flow and the residence times in the post-combustion process. A shorter residence time in experiment V5 with better mixing results in CO, $C_{org.}$, and PCDD/F flue gas concentrations almost identical to those of the V2 experiment. The results of the practical plant support those from investigations carried out in the pilot plant ([40], [41], [42]).

In the field of classical waste combustion, measures for the primary reduction of NO are still being investigated [52]. These measures are connected more strongly with the solid conversion in the bed and the conditions directly over the bed in the combustion chamber than those for the decomposition of CO and organic trace elements. At the beginning of the grate, volatile nitrogenous compounds (NH_i, $N_{org.}$), which can be converted to NO when sufficient oxygen is available, escape from the fuel bed. The conversion of NH_i radicals to HCN proceeds with increasing release of volatile components and formation of CH_4 in particular. These reaction pathways are well-known from batch grate and other experiments [31] and support the assumption that the NO formed can be degraded to N_2 in the presence of NH_i during the NO reduction in the grate unit. However, a higher temperature is required in the grate combustion chamber for this so-called internal “Exxon Process” than for the SNCR process. In order to suppress the conversion of NH_i radicals with CH_4 to HCN, temperatures above 1000 °C are necessary which result in the degradation of CH_4. It can then be concluded that the temperature $\vartheta_{G,gl}$ is an important influencing pa-

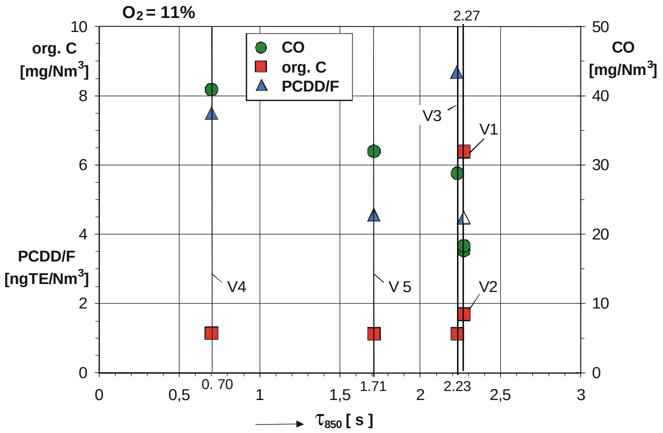


Fig. 19. PIC concentrations (CO, org.C, PCDD/F) of the flue gas in dependence of the residence time of the flue gas t_{850} above 850 °C [39].

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[2] Refer to [39] for more details.

rameter with respect to the release of volatile compounds and the degradation of CH_4 at the beginning of the grate. In addition, the oxygen supply or excess-air ratio has an increasing influence on the determination of an optimal NO/NH_i ratio in the first grate zone.

The effects of the main influencing parameters $\vartheta_{G,gI}$ and λ_{gI} described above were confirmed through tests in a pilot plant.

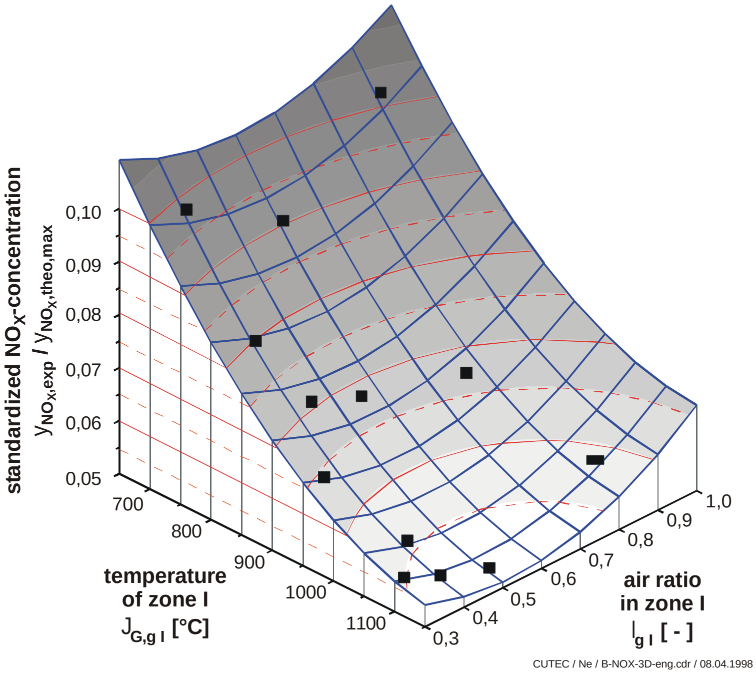

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Fig. 20. Dependence of the NO_X concentration on the temperature $J_{G,gl}$ and the excess-air coefficient l_{gl} during the combustion on the grate [53].

The results are shown in Fig. 20. As expected, the NO values decrease with increasing temperature $\vartheta_{G,gI}$. In addition, local minima in the range of $0.4 < \lambda_{gI} < 0.6$ result for constant temperatures. Reference points supporting these results can be derived from investigations in connection with the NO reduction in a fixed bed gasifier with separate post-combustion [30].

As shown below, an **independent** optimization of the NO reduction, in addition to the optimization of the solid conversion together with other advantages, is achieved when the process control of the post-combustion is clearly separated from that of the grate. Another degree of freedom for an independent post-combustion results from the gasification on the grate and the generation of a combustion gas (possibility of air staging for an independent post-combustion for NO reduction, Fig. 25).

Gasification - Post-Combustion Process

In the separated process control, as shown in Fig. 1, the solid conversion on the grate (1^{st} unit) can be operated understoichiometrically (e.g. $\lambda \approx 0.4$). Due to the above-mentioned control possibilities of grate systems, a complete burn-out of the grate residue (ash) can also be achieved in this mode of operation. The difference to the classical incineration process is the generation of a gas which can be combusted independently in the post-combustion process in the second unit. The second unit can therefore be designed as an independent firing unit. This gasification-post-combustion 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 (Fig. 21),
- combustible gases which enable an independent post-combustion process are generated,
- the post-combustion 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.

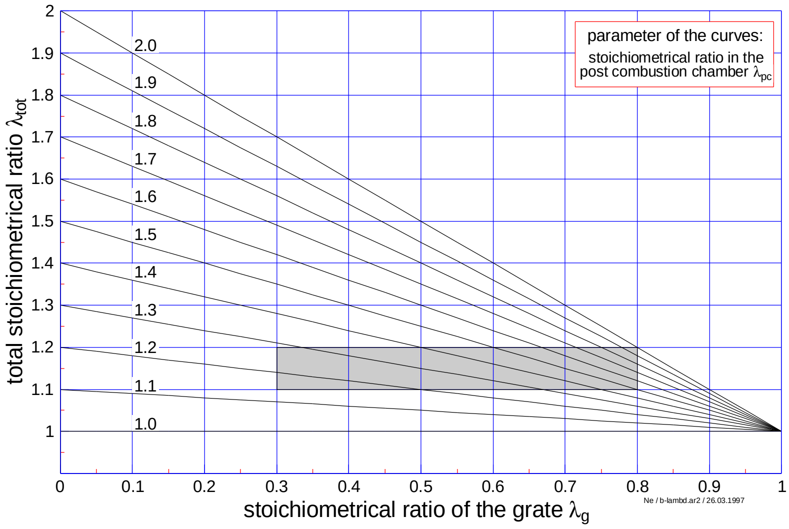

Fig. 21. Dependence of the total stoichiometrical ratio on stoichiometrical ratios of the grate and the post-combustion chamber [18].

These aspects are now explained in detail, with reference to first results at a pilot plant. It should be mentioned, that also an industrial scale plant with a thermal power of 15 MW has been commissioned at the beginning of 2002 [43]. The considerations for the optimization of the process control begun over ten years ago [12] and the results achieved in pilot plant in the mid 1990s ([10], [18]) are supported by results of the recently commissioned industrial plants.

The diagram in Fig. 21 shows that for a separated process control with a stoichiometric ratio of $\lambda \approx 0.4$ to $\lambda \approx 0.6$ for solid conversion on the grate and $\lambda \approx 1.2$ to $\lambda \approx 1.8$ for the post-combustion, total stoichiometic ratios of $\lambda \approx 1.1$ to $\lambda \approx 1.4$ result. The total stoichiometric conditions achieved during the separated gasification-post-combustion process are significantly lower than those for the classical gasification-post-combustion operation ($\lambda \approx 1.6$ to $\lambda \approx 2.0$) resulting in a slower flow velocity in the fuel bed (dust discharge) and a reduction in the flue gas mass flow in comparison with the classical combustion process.

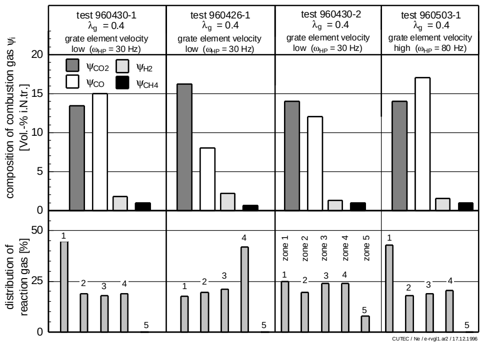

Fig. 22. Comparison of the composition of combustion gas with varying distribution of reaction gas along the grate path and grate element velocity (model fuel wood) [10].

As reported elsewhere [18] 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 material evaporates at the beginning of the grate (Fig. 4). Thus, a heterogeneous decomposition reaction between steam and the hot coke bed is not normal in conventional grate systems. Furthermore, the equilibrium of the homogeneous reaction of CO and H_2O to form 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 following grate zones for gasification. This fact is confirmed by the results presented in Fig. 23, obtained at a pilot reverse-acting grate (0.5 $MW_{thermal}$) ([10], [18]). 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. Fig. 22 shows that the leveling off of hydrogen and methane concentrations ψ is more or less independent of 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 (Fig. 22).

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 (Fig. 23). 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.

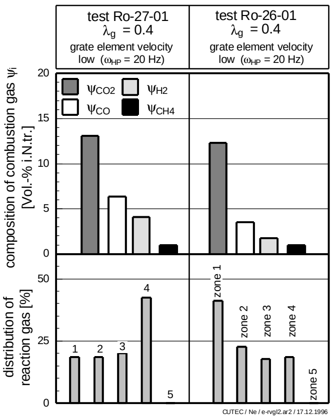

Fig. 23. Comparison of the composition of combustion gas with varying distribution of reaction gas along the grate path (refuse-derived fuel RDF) [10].

As for incineration, residual carbon contents ξ_C of about 1 ma.-% or less can be attained under gasification conditions; thus, coke-like solid residues are avoided. For 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 Fig. 24. With respect to 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), local overstoichiometrical conditions regarding the remaining carbon can nevertheless be adjusted in the area of the burn-out zone, if necessary.

Marked differences result between process conditions of the gasification and incineration mode with regard to the formation of flue dust. The significantly lower mass flow of air resulting from the operation under gasification conditions compared to those resulting from the superstoichiometrical operation causes a corresponding reduction of flow velocities through the combustion bed. The expected tendency, that a decreasing stoichiometric ratio causes the formation of less flue dust, is confirmed in Fig. 24.

The gases generated by gasification in the grate process are supplied to the post-combustion chamber. The heating value is about $h_n \approx 1500$ kJ/kg to $h_n \approx 2500$ kJ/kg and temperatures reach levels of $\vartheta \approx 750$ °C to $\vartheta \approx 1000$ °C depending on the stoichiometric air ratio of the grate process. If the post-combustion chamber is well insulated with a refractory jacket, the post-combustion process runs independently without additional fuel. Well-known primary measures to minimize pollutants can then be applied (e.g. [25] to [29]). Consideration is given here to NO minimization with a simultaneous reduction of the CO concentration. First of

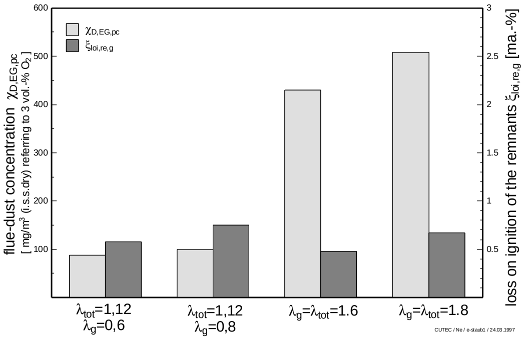

Fig. 24. Flue dust concentration before flue gas cleaning and loss of ignition for different stoiciometric ratios in the stoker system [18].

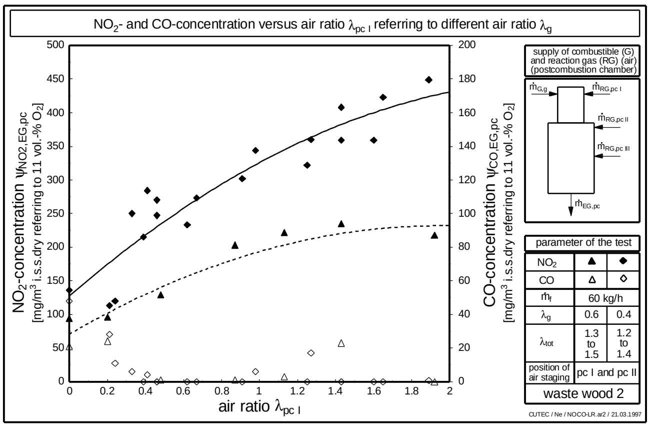

Fig. 25. NO_2 and CO concentration versus air ratio $l_{pc\,I}$ (different air ratio l_G in the grate unit) [18].

all, the stoichiometric ratio of the gasification process affects the NO emission.

Fig. 25 shows the NO and CO emissions of a staged combustion of the combustible gas generated at the grate for a 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. An increase of the primary air ratio is accompanied by a temperature increase from about $\vartheta \approx 700$ °C to about $\vartheta \approx 1000$ °C. Furthermore, an increase of the oxygen supply results. With this, a higher decomposition of volatile nitrogen components such as HCN and NH_i via NO and a reduction of already formed NO via the “NO recycling“ path is more probable. In addition to the influence of the primary air ratio, the NO concentrations in Fig. 25 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/m³ for a single-staged post-combustion to 200 mg/m³ for a twofold-staged post-combustion (air supply in stage I and II) with $\lambda_{PC\,I} \approx 0.5$, whereby the CO concentration is far below 10 mg/m³. 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/m³ to about 120 mg/m³. For a twofold-staged post-combustion, a further NO reduction below 100 mg/m³ results when air is fed into the first and the third stage of the combustion chamber whereby the CO concentration remains below 10 mg/m³ [32]. The further NO reduction here is due to the longer residence time in connection with higher temperatures and lower oxygen concentrations in the understoichiometric first stage. Furthermore, if air is fed to the third stage, nearly plug flow conditions prevail in the understochiometric part after the enlargement of the post-combustion chamber, which is preferable for NO reduction steps [29].

Efficiency

In order to conclude the section covering the classical waste combustion, the determination of efficiencies for the individual partial processes and for the total process will be discussed. Within this framework, the representation can only be summarized here. The description of operations through the determination of efficiencies can also be applied correspondingly to the process assessment using other evaluation criteria such as the balance of the specific CO_2 or pollutant discharge. The efficiency describes the relationship between use and expenditure. Depending on what is regarded as use or expenditure, very different efficiencies can result. It is therefore very important to differentiate between certain efficiencies according to the accompanying balance limits for the assessment of processes and process chains. The difference between certain efficiencies is illustrated in Fig. 26.

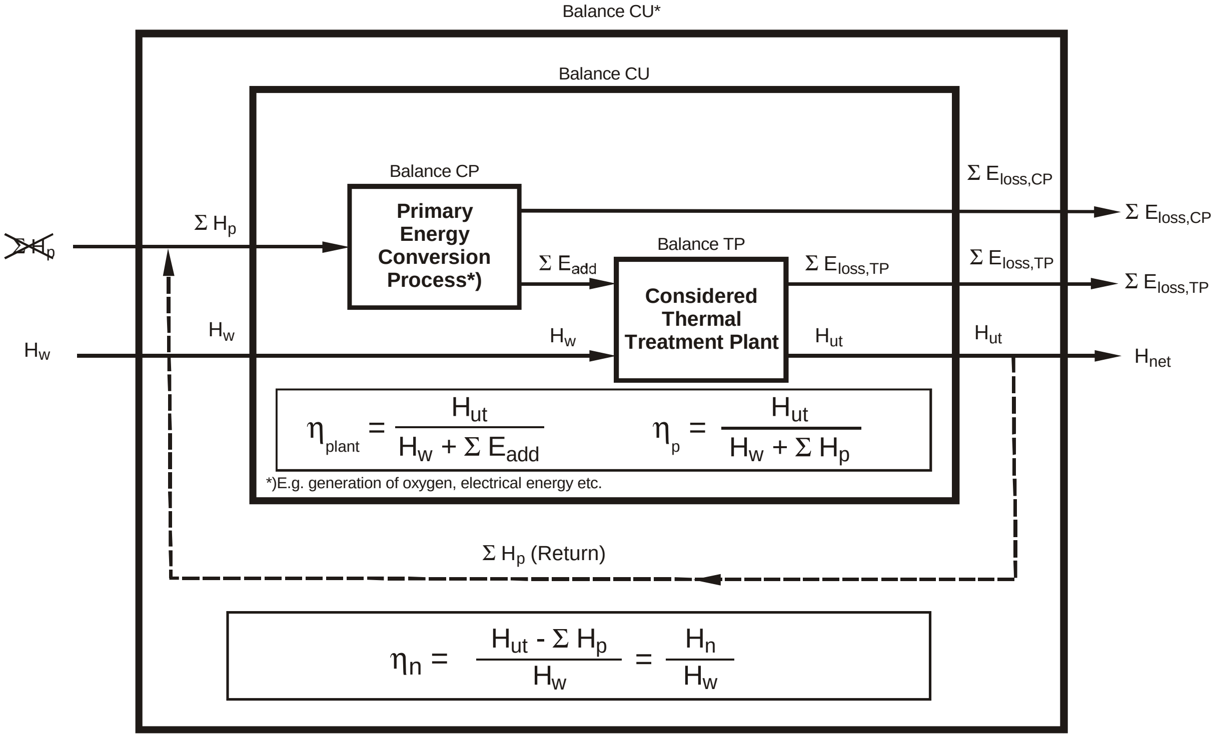

Fig. 26. Simplified energy balance to illustrate the plant efficiency h_{Plant}, the primary efficiency h_p and the net primary efficiency h_n.

The waste energy H_w[3]) and the supplemental energy required ΣE_{add} is added to the balance room TP (Treatment Plant, TP) of the plant being in consideration. The plant then releases the effective energy H_{ut} and the sum of the energy lost $\Sigma E_{loss,TP}$. The so-called „plant efficiency" is then

$$\eta_{Plant} = \frac{H_{ut}}{H_w + SE_{add}} \tag{3-1}$$

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[3]) Generally, energy is represented as flow or stream. In the following considerations, the absolute energy per 1000 kg waste (MJ/Mg_{waste}) and the capital letters (H, E, etc.) are chosen.

When, in addition to the energy supplied for the operation of the plant ΣE_{add}, the energy lost $\Sigma E_{loss,CP}$ during the corresponding conversion process is regarded as expenditure (balance room CP), i.e. the **total** primary energy ΣH_p required for the operation of the plant is viewed as expenditure, for example, primary energy for the supply of electricity, for an eventual oxygen generation, for the production of operating substances and additives, etc., then a cumulative balance room CU and the so-called primary efficiency from the ratio of success to expenditure results

$$\eta_p = \frac{H_{ut}}{H_w + \Sigma H_p} \quad , \qquad (3\text{-}2)$$

which can be significantly lower than the plant efficiency η_{Plant}. When considered in this manner, we are dealing with a so-called „cumulative“ representation of the most important process units connected in front or perhaps afterwards. Starting points for the cumulative consideration are the necessary primary energy and the raw materials for the thermal treatment of the waste. The end point of the consideration is then at the balance limit where the environmentally acceptable deposition of remaining materials and/or the implementation of residual valuable materials in a recycling process is possible.

The primary energy consumption necessary for the treatment could be saved if no waste existed. A „waste use“ H_n can be created in which the primary energies necessary ΣH_p are subtracted from the effective energy H_{ut}. The primary resource is then replaced by the „self-generated“ effective energy or substituted or mentally recirculated[4], as shown by the dashed-lines in Fig. 26. Only the supplied waste energy H_w remains as expenditure and the net energy H_n as use so that the so-called net primary efficiency results

$$\eta_n = \frac{H_{ut} - \Sigma H_p}{H_W} = \frac{H_n}{H_W} \quad \text{in the case } (H_{ut} - \Sigma H_p) \geq 0 \qquad (3\text{-}3)$$

For the primary energy substitution (recirculation), the balance limit is marked with an „*“ (Fig. 26 also „CU*“).

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[4]) It must be mentioned here that the substitution of one type of energy (e.g. natural gas enthalpy) through another (e.g. generated vapor enthalpy) can generally not be carried out at a 1:1 ratio. This means that the amount of energy to be substituted (e.g. bound to the natural gas) can generally not be substituted through an equal amount of substitute energy but through a higher amount (e.g. bound vapor). This behavior is described through the so-called energy exchange ratio E_R as the ratio of substitution energy to energy to be substituted. Usually $E_R > 1$ and is dependent upon many factors. For clarity, $E_R = 1$ in order to illustrate the principle of substitution or the energy recirculation. The determination of E_R is covered in [1], [33], [34], [35].

In the case of a high necessary primary energy supply, the difference $(H_{ut} - \Sigma H_p)$ for the formation of the net energy can also be a negative value, i.e. more energy is required for the treatment of the waste than the waste itself adds to the process. In this case, the definition of the efficiency is negative. Therefore, such cases are regarded as degrees of expenditure. As reference value, $\left| H_w - H_n \right|$ is chosen, i.e. the degree of expenditure a is defined as

$$a = \frac{H_{ut} - SH_p}{H_w + \left| H_{ut} - SH_p \right|} = \frac{H_n}{H_w + \left| H_n \right|} \quad \textit{in the case } (H_{ut} - SH_p) < 0 \qquad (3\text{-}4)$$

, so that the smallest value for the degree of expenditure assumes $a_{min} = -1$ for reasons of formality.

In the following section, these efficiencies will be calculated for the example of the classical waste combustion. A significant prerequisite for the process evaluation is the systematic representation of partial processes with the determination of the balance limits and the respective material and energy flows which enter and leave in the balance circles. For thermal waste treatment processes, it has proved suitable to divide the first step of the total process into the partial steps of the so-called main thermal process and the flue gas purification and energy conversion (see Fig. 2). With the help of the overview in Fig. 1 for the systematic description, the main thermal process of the classical waste incineration can be illustrated as a combustion unit (1st unit) and post-combustion (2nd unit). A generation of effective thermal energy in the reactor is coupled with both units with respect to the balancing. It can be practical to include a possible post-treatment of the residual material in the first balance circle when comparing processes with an integrated melting of the residues (e.g. high temperature gasification) for example. This then leads to a first balance circle A, as shown in Fig. 27, which contains the main thermal process with effective thermal energy.

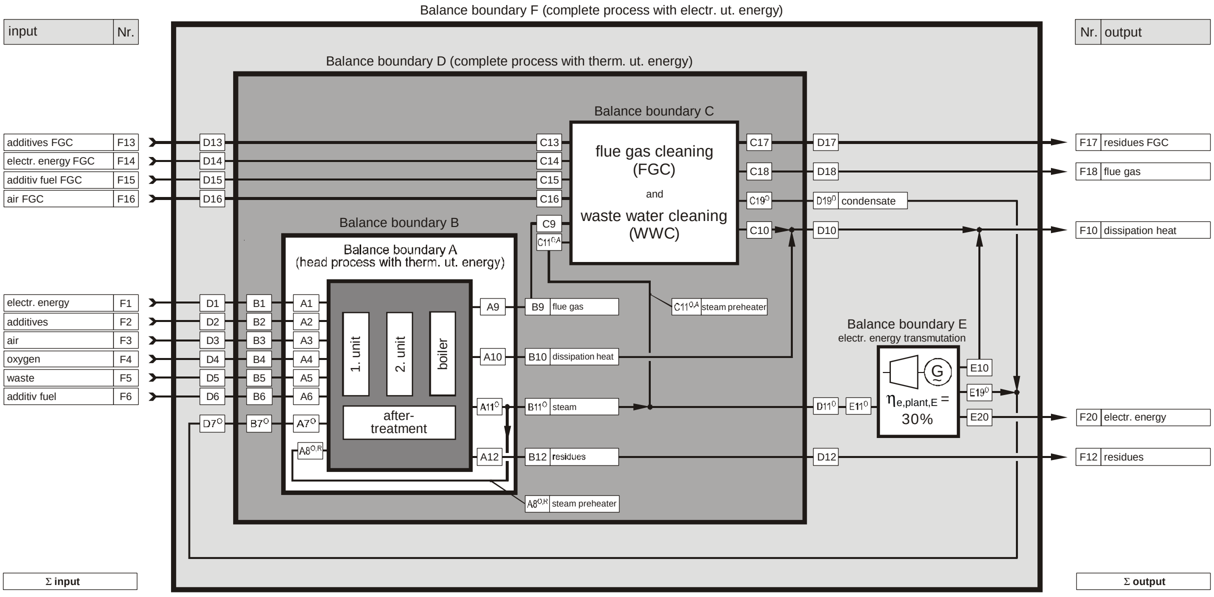

Fig. 27. Block flowchart of a classical household waste incineration (here with oxygen enrichment of the combustion air) [1].

The balance limit B encompasses the balance room A with an internal recirculation of the effective thermal energy, e.g. for the preheating of the air [1]. The flue gas and waste water treatment are included in the balance circle C. Together, the balance circles of the main thermal process B and the flue gas/waste water purification C form the balance circle of the total process D with the aim of the decoupling of the effective thermal energy. If D is expanded to included the balance circle E, which contains the steam process, then the total process, with the goal of the electrical decoupling of the effective energy in balance circle F, results. Processes in balance circle F arranged in series before or after are of significance during the evaluation of waste treatment. These so-called cumulative viewpoints can be achieved through the expansion of the balance circles and the fictional supplementation of each process (e.g. the energy conversion in a power plant or the oxygen generation in an air-separation unit). Next, the material balances (material, mass and energy balance) must be created for the individual balance circles. The energy balance then forms the basis for the determination of individual and total efficiencies. Fig. 28 shows such an energy flow diagram for the case of a waste material with a low heating value ($h_n = 6$ MJ/kg). As mentioned before, the balance limit F was expanded through the addition of the processes for the oxygen generation and the primary energy conversion. The balance limit K then contains the total process with effective electrical energy and the consideration of the additional primary energy expenses.

Based on the systematic determination for the balance circles and the corresponding energy balances, it is now relatively easy to form the characteristic single and total efficiencies (basic description in Fig. 26). With the current definition of the efficiency:

η = use/expenditure, the following thermal plant efficiency for the balance room A results:

$$\eta_{t,plant,A} = \frac{use}{expenditue} = \frac{H_{A11^O}}{S(H_{A1} bis\ H_{A6}) + H_{A7^O} + H_{A8^{O,R}}} = 72{,}2\% \, , \qquad (3\text{-}5)$$

In the same way, the thermal plant efficiencies for consideration of the preheating of the air (balance circle B) and for the total process (balance circle D) can be determined. The values from Fig. 28 are plotted in Fig. 29 as an example. Using the efficiency of the energy conversion from high-pressure steam to electrical energy (in this case $\eta_{e,plant,E}$ = 30 %, balance circle E), the electrical plant efficiency for the total process (balance room F; decoupling of effective electrical energy) results as:

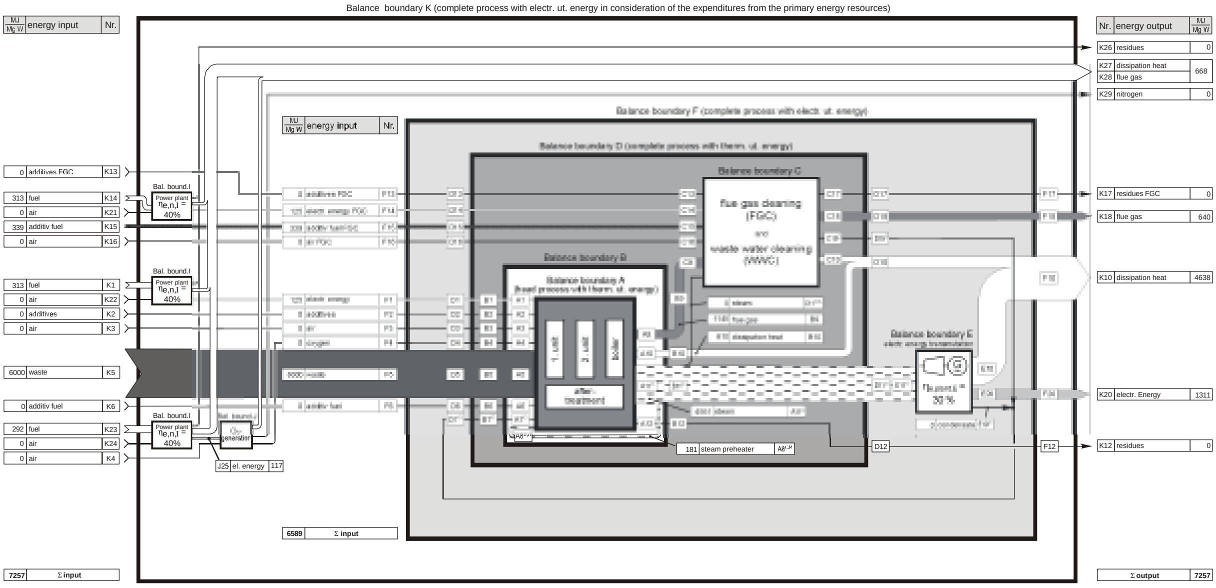

Fig. 28. Simplified energy flow diagram of the classical household waste incineration with regard to the primary energy resource expenditure (here with oxygen enrichment of the combustion air) [1].

$$\eta_{e,plant,F} = \frac{use}{expenditure} = \frac{E_{F20}}{S(H_{F1} bis\ \ H_{F6}) + S(H_{F13} bis\ H_{F16})} = 19{,}9\,\% \qquad (3\text{-}6).$$

Assuming an electrical efficiency for the electricity supply of $\eta_{e,n,I}$ = 40 % and a specific expenditure for the oxygen generation of 1.08 MJ electrical energy / kg oxygen, the additional expenditure in the form of the thermal and electrical primary energy efficiency can now be determined:

$$\eta_{e,p,K} = \frac{H_{E11^{O}} \cdot ?_{e,a,E}}{S(H_{K1}\,\mathit{bis}\,H_{K6}) + S(H_{K13}\,\mathit{bis}\,H_{K16}) + S(H_{K21}\,\mathit{bis}\,H_{K24})} = 18{,}1\,\% \,. \qquad \text{(3-7).}$$

In the above-mentioned example, the primary thermal efficiency for the balance room K results under the assumption that the electrical energy conversion (balance room) is omitted.

The primary energy could be saved or could supply a higher quality utilization in other processes, if no waste to be treated existed. This consideration leads, together with the explanation to Fig. 27, to the net primary efficiency. For the example in Fig. 28, the following net primary electrical efficiency results:

$$\eta_{e,n,K^*} = \frac{(H_{A^*11^{O}} - H_{A^*8^{O,R}} - H_{D^*11^{O,R}}) \cdot ?_{e,a,E^*} - E_{E^*20^{R}} - E_{F^*20^{R}}}{S(H_{K^*2}\,\mathit{bis}\,H_{K^*5}) + H_{K^*13}} = 14{,}0\,\% \,. \qquad \text{(3-8)}$$

Balance circle	**Efficiency**	**Energy use** [MJ/kg W]	**Specific flue gas mass** [Mg/Mg W]	**Specific CO_2 mass** [Mg/Mg W]
Balance circle A Main process with therm. ut. energy	$\eta_{t,plant,A}$ = 72,2 %	4551	4616	641
Balance circle B Main process with therm. ut. energy and steam recirculation	$\eta_{t,plant,B}$ = 71,3 %	4370	4616	641
Balance circle D Complete process with therm. ut. energy	$\eta_{t,plant,D}$ = 66,3 %	4370	4780	660
Balance circle K Complete process with electr. ut. energy in consideration of the expenditures from the primary energy resources	$\eta_{t,p,K}$ = 60,2 %	4370	5223	748
Balance circle K* Complete process with therm. ut. energy and recirculation of the expenditures from the primary energy resources	η_{t,n,K^*} = 46,8 %	2807	4633	641
Balance circle F Complete process with electr. ut. energy	$\eta_{e,plant,F}$ = 19,9 %	1311	4780	660
Balance circle K Complete process with electr. ut. energy in consideration of the expenditures from the primary energy resources	$\eta_{e,p,K}$ = 18,1 %	1311	5223	748
Balance circle K* Complete process with electr. ut. energy and recirculation of the expenditures from the primary energy resources	η_{e,n,K^*} = 14,0 %	842	4633	641
Boundary conditions				
Initial net calorific value of the waste			$h_{n,W}$	= 6 MJ/kg
Preheating of the reaction gas			ϑ_A	= 120 °C
O2 concentration			$\Psi_{O2,RG}$	= 23.9 vol.-%
Stoichiometric ratio			λ	= 1.9
Treatment temperature			ϑ_G	= 1000 °C
Flue gas temperature after boiler			$\vartheta_{G,B}$	= 220 °C
Flue gas temperature after flue gas cleaning			$\vartheta_{G,FGC}$	= 60 °C
Flue gas temperature after reheating			$\vartheta_{G,RH}$	= 120 °C
Efficiency of electrical energy conversion			$\eta_{e,plant}$	= 30 %

Fig. 29. Exemplary representation of the evaluation of waste treatment (for examples see Fig. 28 and text) [1].

A waste with a very low heating value (h_n = 6 MJ/kg) is chosen for the example in Fig. 28. The heating value of the waste has a critical influence on the process control of the waste incineration plant and affects the efficiency of the plant correspondingly.

Fig. 30 shows the dependence of efficiency determined above upon the initial waste heating value $h_{n,W}$. In order to maintain the required temperature (here the process temperature of the post-combustion) for decreasing initial waste heating values, the measures „λ reduction“, „oxygen enrichment“ and „supplementary fuel“, often applied practically, are compared with one another as shown in Fig. 30. The primary electrical efficiency $\eta_{e,p,K}$ = 19 % and the net primary efficiency η_{e,p,K^*} = 17 % can be read out of the diagram in Fig. 30 for initial waste heating values of $h_{n,W}$ = 10 MJ/kg, which is normal for middle European cities.

It should be mentioned, with regard to the cumulative balances, that negative energy balances can also result, e.g. the processes consumes more energy (with reference to the primary energy) than is generated through the waste treatment. It is in this case no longer a degree of efficiency but a corresponding degree of expenditure [1].

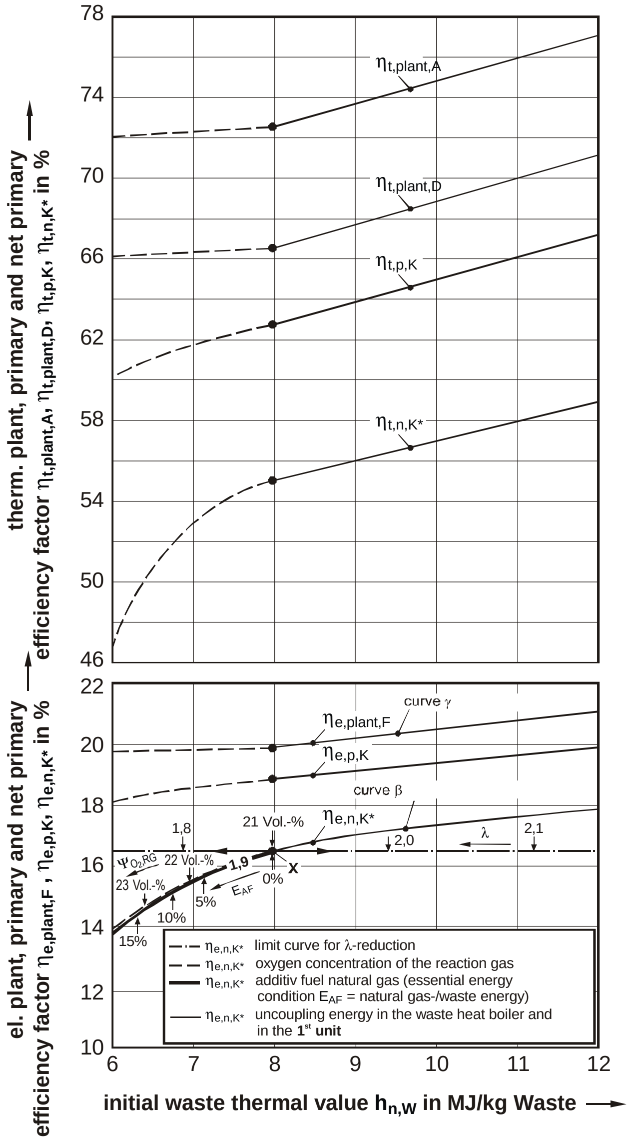

Fig. 30. Electrical plant, primary and net primary efficiency ($h_{e,plant,F}$; $h_{e,p,K}$ and $h_{e,n,K*}$) dependent upon the initial waste heating value $h_{n,W}$ for various measures (classical waste incinerator; flue gas temperature $J_{G,PC}$ = 1000 °C) (explained in the text) [1].

List of Symbols

SYMBOLS

a	inert gas rate
a	degree of expenditure
A/B	partial flow A and B
A-K	balance circle number, efficiency
CSR	continuously stirred reactor
E	energy, energy exchange ratio
h	specific enthalpy (heat of combustion)
h	calorific value
H	enthalpy
$\dot{m}$	mass flow
Mg	1000 gram = 1 ton
MW	municipal solid waste
oxi.	oxidizing conditions
p	pressure
Pe	Peclet-Number
PFR	plug flow reactor
T	temperature [K]
ut	utilization
V	number experimental setting
vol.	volume
w	water-content
w	velocity
x	stream x
y	stream y
Δ	difference
ϑ	temperature [°C]
λ	stoichiometric ratio, excess-air coefficient
ξ	concentration (mass-related)
ψ	concentration (volume-related)
ω	frequency
τ	residence time
χ	concentration

INDICES

0	starting value
I / II	grate zone
add	additive
A	air, reaction gas
A-K	balance circle number, efficiency
b	beginning
B	fuel
B	boiler
C	carbon
CP	conversion process
CU	cumulative
D	dust
e	electrical
e	end
eq	equivalent
exp	experimental
F	flue dust
FGC	flue gas cleaning
g	grate
G	fuel gas/flue gas
HP	hydrogen pump
i	ignition
in	inert
i.s.s.d./i.s.s.dry	under standard conditions, dry
lo/loss	loss
loi	loss of ignition
max	maximum
min	minimum
n	net (lower) heating value, net (usable) Enthalpy, net primary efficiency
p	primary
pc/PC	post combustion chamber
plant	plant
R	ratio (energy exchange ratio)
re	remnants
Re	residue
RG	reaction gas
RH	reheating
S	solid
t	thermal
theo	theoretical

tot	total
TP	treatment process
u	use
w/W	waste
x	stream x (post-combustion)
y	stream x (post-combustion)
*	recirculation of generated energy for substitution fuel

Notations

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used in the concrete field. High deposit fees would further stimulate the investigations and process optimisations.

To increase the properties, particularly the reactivity, of further thermally treated MSWI-slag, several methods exist (based on [54] with additions):

- Increased fineness (> 5000 cm^2/g), though this is rather expensive
- Increased amount of reactive (vitreous) components in the MSWI through e.g. appropriate quenching
- Further reduction of the heavy metal content
- Forced weathering of the mineral components through, e.g. longer storage under advantageous conditions
- Devitrification (zeolitisation) of glasses
- Altered composition of the input material in MSWI through the addition of appropriate materials or omission of waste fractions; in general the higher the ratio $CaO : SiO_2$, the higher the reactivity

3.5.5 Conclusions and Outlook

Large amounts of further thermally treated MSWI-slag are produced nowadays and the tendency, at least in Europe, is toward continual increase. In the building material industry, large amounts of materials are used (exploited from nature). Therefore, at first glance it seems most rational to investigate whether further thermally treated MSWI-slag can be used in the building material sector to reduce the use of natural resources. Based on investigations thus far, further thermally treated MSWI-slag is mainly inert in cementitious materials during the investigations over 90 days. In order to create a higher level of benefit from further thermally treated MSWI-slag, a pozzolan or latent hydraulic reactivity would be desirable. The optimisation of new processes at MSWI plants with respect to the quality of the further thermally treated MSWI-slag is strongly recommended.

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