Beckmann, M.; Scholz, R.; Horeni, M.: Using Substitute Fuels in the Basic Materials Industry. In: Ludwig, Ch.; Hellweg, S.; Stucki, S.: Municipal Solid Waste Management – Strategies and Technologies for Sustainable Solutions. Springer-Verlag, 2002. S. 196-204. ISBN 3-540-44100-X

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ISBN 3-540-44100-X Springer-Verlag Berlin Heidelberg New York
Library of Congress Cataloging-in-Publication Data Applied For

Die Deutsche Bibliothek – CIP Einheitsaufnahme
Municipal solid waste management : strategies and technologies for
sustainable solutions / Christian Ludwig ... (ed.). - Berlin ; Heidelberg ;
New York; Hong Kong ; London ; Milan ; Paris ; Tokyo :
Springer, 2003
ISBN 3-540-44100-X

Springer-Verlag Berlin Heidelberg New York
a member of BertelsmannSpringer Science+Business Media GmbH

http://www.springer.de

Printed in Germany

Camera ready by editors
Cover design: E. Kirchner, Heidelberg
Printed on acid-free paper SPIN 10831526 30/3130/as 5 4 3 2 1 0

After a period of over 20 years in which emission control was the main focus, now optimisation of the reuse of emissions will be the name of the game, including fixed materials (ashes, iron, non-ferro, etc.) as well as the energy in the waste.

Innovative thinking characterises the construction of this high efficiency boiler, and with it a whole new generation of waste incineration plants. Recognition of this thinking has already come in the form of a EU subsidy for the boiler.

5.1.3 Using Substitute Fuels in the Basic Materials Industry

Michael Beckmann, Reinhard Scholz, and Martin Horeni

Various approaches to improving energy recovery from MSW have been discussed. The one described here involves separating fractions with high heating value, known as substitute fuels e.g. RDF, (see 4.1, 5.1) for efficient conversion. The material and energetic utilization of such fractions is being applied to an increasing degree in the production of basic materials (cement, lime, steel industry, etc.).

A series of investigations to find ways of optimizing process control using substitute fuels rather than fossil fuels have been carried out in high-temperature production processes, such as the clinker calcining process, and in the field of energy conversion in power plants. From these investigations fuel technology criteria appropriate for the individual processes have been derived. According to fuel technology, a fuel is characterized by its chemical, mechanical, caloric and reaction technological properties. Based on these properties, a corresponding classification for the substitute fuel can be made, similar to the classification of conventional primary fuels, such as fuel gases, heating oils and coal.

The differences between the ignition and burn-out behaviors of substitute fuels and conventional fuels with a substitution rate of e.g. 1 to 5 % generally have no significant effects on the process. The following statements concerning the requirements for substitute fuels therefore refer to a significant substitution rate in the range of 20 % and more. Since there is little empirical data on the fuel technology properties of substitute fuels, e.g. they have not been systematically characterized, these must be inferred from practical experience with various conventional fuels. Moreover, the process control may also have to be adapted when using substitute fuels. When substitute fuels are used, the boundary conditions change, and the following topics must be addressed:

- process optimization;
- energy recovery by internal and external energy combinations;
- examination of the process chain with cumulative material, mass and energy balances in the sense of the total analysis.

Substitute fuels are, as the name suggests, used to substitute conventional fuel materials (fossil fuels) in power plant and process combustion. Therefore, the total process chain (including expenditure on the production of substitute fuels from

MSW), must present energetic advantages over the reference case of using conventional fuels in the individual processes, and incinerating unsorted waste in a municipal solid waste incineration plant. Approaches to producing and using substitute fuels selected from the energetic point of view must then be assessed with respect to emissions and profitability. Fuel properties alone do not suffice for the evaluation of a substitute fuel.

After a comprehensive description of the fuel technology properties of substitute fuels, findings about their significance from an energetic point of view will, therefore, be presented. In this case, the so-called energy exchange ratio, i.e. specific energy consumption and efficiency, has to be considered. When evaluating the use of a substitute fuel, the process chains, consisting of the substitute fuel production process (e.g. mechanical-biological pre-treatment, MBP), the process for the utilization of the substitute fuel (e.g. production process) and the process for the treatment of the remaining residual fraction from the substitute fuel production (e.g. thermal waste treatment, dumping), must be examined [35, 204, 207].

Fuel Properties

An evaluation of the chemical, mechanical and reaction kinetic properties of substitute fuels depends upon empirical results (e.g. [95, 103, 117, 150, 192]). As described in [35], the interaction between the main influencing parameters can be demonstrated with the help of simplified, but effective, practical mathematical models of the caloric properties.

The **chemical properties** of conventional fuels are divided into noncombustible (ash, water) and combustible substances in the fuel. This classification can be transferred directly to substitute fuels. The combustible substances can then be divided into plastics and other organic components, which is useful for a comparison of the processes. Furthermore, the element and trace element composition, the proportion of the organically bound and volatile components and the ash-melting temperature can be viewed as chemical properties. These properties can, of course, also be used in evaluating substitute fuels.

The so-called trace element contents (heavy metals, chlorine, phosphorus, sulfur, etc.) also belong to the category of chemical properties. The trace elements are particularly important in the evaluation of emissions and product quality.

The **mechanical properties** of conventional and substitute fuels consist of: the density of the combustible and noncombustible substances, flow properties, grindability, grain-size distribution and general handling with respect to the storage (mechanical) and feeding of the fuel to the plant (burner, etc.).

The **caloric properties,** such as heating and calorific value, specific minimum air requirement, specific minimum amount of flue gas, adiabatic combustion temperature, heat capacity, thermal conductivity, etc. can, as with conventional fuels, also be used with substitute fuels.

Assessing the **reaction technology properties** of waste materials is more difficult than for conventional fuels. Reaction technology properties are basically dependent upon the chemical, mechanical and caloric characteristics of the fuels. Since the early 1930s, investigations of the ignition and burn-out rate in dependence upon e.g. the quantity of volatile components, the grain size or the heat transferability, thermal conductivity, etc. have been carried out for conventional fuels. A series of mathematical models and corresponding data concerning the reaction coefficients, pore radius distribution, activation energy, diffusion coefficients, etc. are available. For substitute fuels, which have a more heterogeneous and variable composition than conventional fuels, it is possible to use a simplified model to describe the burn-out with cumulative kinetic parameters determined with a special experimental apparatus (e.g. batch reactor, thermobalance). An additional criterion, closely related to the reaction technology properties, concerns the storage life, which should be examined from more than just a purely mechanical standpoint.

When assessing the above-mentioned criteria it is important to consider the technical process that the fuel is to be applied to. Questions concerning the process optimization and energy recovery by internal and external energetic combinations for the altered boundary conditions with fuel substitution must be answered. The various energy exchange ratios will be discussed in the following section.

Energy Exchange Ratio in the Partial Steps of the Substitution

If a certain amount of the primary fuel PF (e.g. hard coal) is replaced by a substitute fuel in a partial process (e.g. main combustion in the cement clinker calcining process, melting process of iron scrap), then the process as a whole, with respect to the production goal (e.g. clinker brick production and quality, melting capacity), should remain unchanged. This means that the solid temperature ϑ_s and the furnace capacity, e.g. the transmitted heat flow $\dot{Q}$, must, from the point of view of heat-engineering, remain constant. The energy exchange ratio E:

$$E = \frac{\dot{m}_{SF} \cdot h_{n,SF}}{\dot{m}_{PF} \cdot h_{n,PF}}$$

expresses the energetic significance of the substitute fuel (SF) relative to the primary (conventional) fuel (PF). With the help of simplified mathematical models of the balancing and heat transfer in the furnace chamber (e.g. [35], the energy exchange ratio, e.g. as a function of the corresponding gas temperature, is determined for given boundary conditions (in particular, heating values for the primary and substitute fuel, preheating of air and fuel, gas temperature, solid temperature) as shown in Figure 5.21.

The energy exchange ratio E (Figure 5.21) increases, the higher the temperature to be reached and the lower the heating value of the substitute fuel in comparison with the primary fuel. Where the heating value of the substitute fuel is greater than that of the primary fuel, the energy exchange ratio assumes values less than one. This happens, for example, when hard coal is replaced with high-calorific plastic waste during the primary combustion in the clinker calcining process.

Energy Exchange Ratio for the Total Process

The influence of air preheating can be seen from the curves for the energy exchange ratio E of the partial processes Figure 5.21. When we compare two processes in which a substitute fuel with $h_{n,SF\ I} = 20$ MJ/kg (SF I) and no air preheating is combusted in the first process and a substitute fuel with only $h_{n,SF\ II} = 15$ MJ/kg (SF II) but with air preheating in the second, then, at process temperatures of $\vartheta_G > 1600$ °C, the substitute fuel SF II has "more value" than the higher-calorific SF I. This shows that the energy exchange ratio is clearly not only dependent upon the caloric characteristics of the fuel, but is also influenced significantly by the process control and optimization, e.g. through improved heat recovery.

During the preheating of the air and fuel, the fact that the efficiency of the heat recovery is determined substantially by the minimum air requirement l_{min} and the corresponding excess-air ratio λ [e.g. 220] must be taken into account.

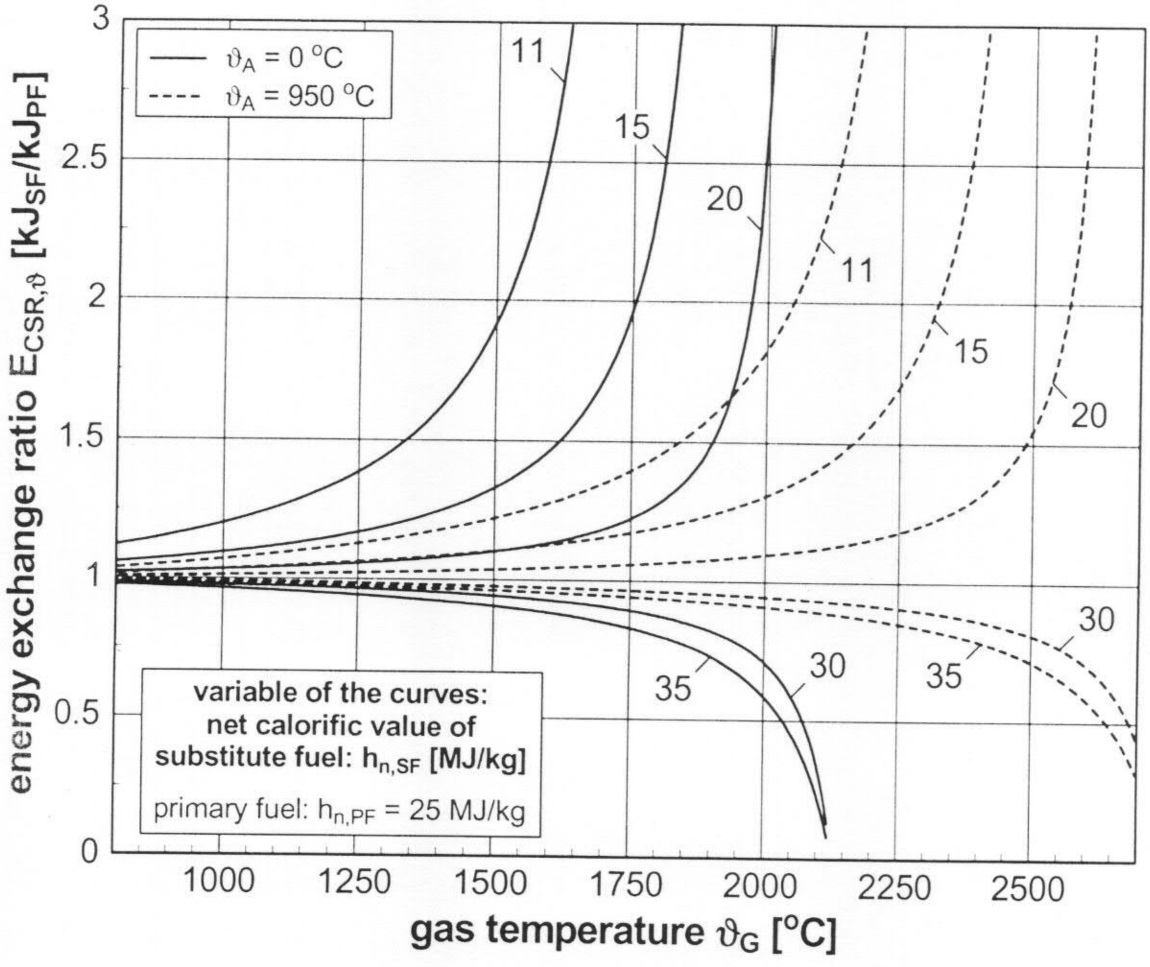


Fig. 5.21. Energy exchange ratio for statistical evaluation [35]

Another characteristic feature which must be considered with regard to the energy exchange ratio of the total process is that the minimum air requirement l_{min} and the minimum amount of flue gas v_{min} do not decrease at the same rate as the heating values $h_{n,SF} / h_{n,PF}$. For solid fuels, the minimum amount of flue gas can be approximated by statistical combustion calculation [42]. If a constant specific energy requirement for the process is assumed, then the ratio of the minimum flue gas concentration from the substitute fuel to that of the primary fuel $v_{min,SF} / v_{min,PF}$ can be approximated dependent upon the heating value ratio $h_{n,SF} / h_{n,PF}$. The specific energy requirement of the total process increases primarily with the flue gas flow rate. In this case, a reduction of the specific energy requirement is necessary e.g. through heat recovery (preheating of the air or fuel, utilization of the heat lost for other processes, etc.).

Another possibility is for the heat recovery to be made process-internal, e.g. by adjusting the process control by changing the ratios of heat capacity flows or by fuel staging. Fuel staging is particularly effective for processes that are clearly divided into several partial steps, each with different temperatures (e.g. preheating, de-carbonisation, combustion or melting, overheating of the melt). If a relatively high energy exchange ratio results, e.g. from the requirements for the combustion process with a corresponding high temperature for a partial process (i.e. the energy input when using the substitute fuel must be higher than when using the primary fuel), then a portion of the additional energy input can be "recovered" in the subsequent partial steps dependent upon the temperature in the partial processes (i.e. the energy input in the following partial step, e.g. de-carbonisation of raw material, can then be minimized). For the total process, markedly reduced energy exchange ratios with values only a little above unity can result. The usable enthalpy flow in the subsequent partial process is, as mentioned above, dependent upon the temperature of the partial step, which is determined independent of the input of substitute fuel.

At this point it should be mentioned that fuel staging, such as in the cement clinker calcination process, is possible.

As shown in the plant scheme in Figure 5.22, the fuel is added at three feed points: the main firing (furnace discharge, I in Figure 5.22), the second firing (calcinator, II) and the supplementary firing at the furnace entrance (III). Theoretically, substitute fuel can be added at all of the three feed points if certain specific boundary conditions are considered. Figure 5.23 shows the results of a simplified but effective mathematical model of the energy exchange ratio $E_{CSR1,\vartheta}$ as a function of $h_{n,SF}$ for the substitution of a primary fuel in the main firing chamber (I) with $h_{n,PF} = 25$ MJ/kg, a balance temperature of $\vartheta_{G1} = 1.900$ °C and with air preheating to $\vartheta_A = 950$ °C. Furthermore, the curve for $E_{CSR2,\vartheta}$ for the second firing (II) is plotted for a certain balance temperature, which, due to the saving of primary energy for the substitution presented here, reaches values less than one. $E_{CSR12,\vartheta}$ is generally greater than one, but as a resulti of the staged fuel input, significantly lower than $E_{CSR1,\vartheta}$.

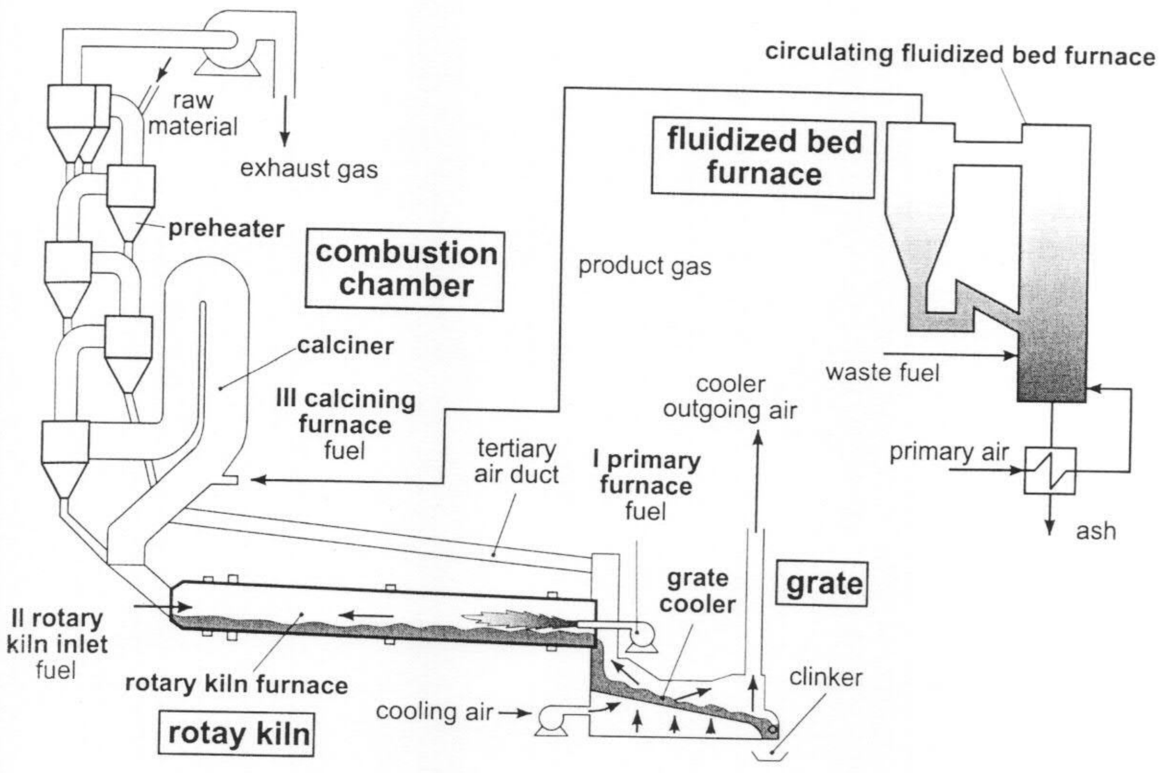


Fig. 5.22. Schematic representation of the clinker brick calcination after the drying process with the calcinator and extermal gasification in a circulating fluidized bed (CFB)

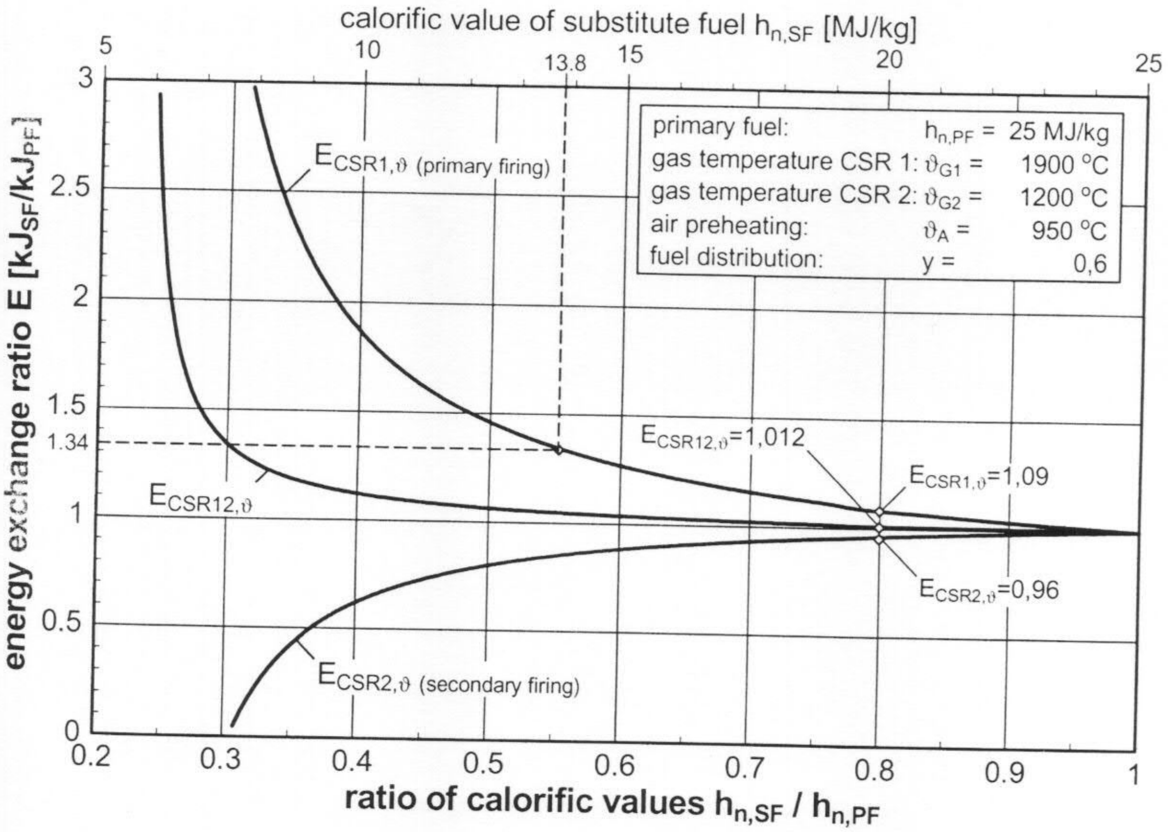


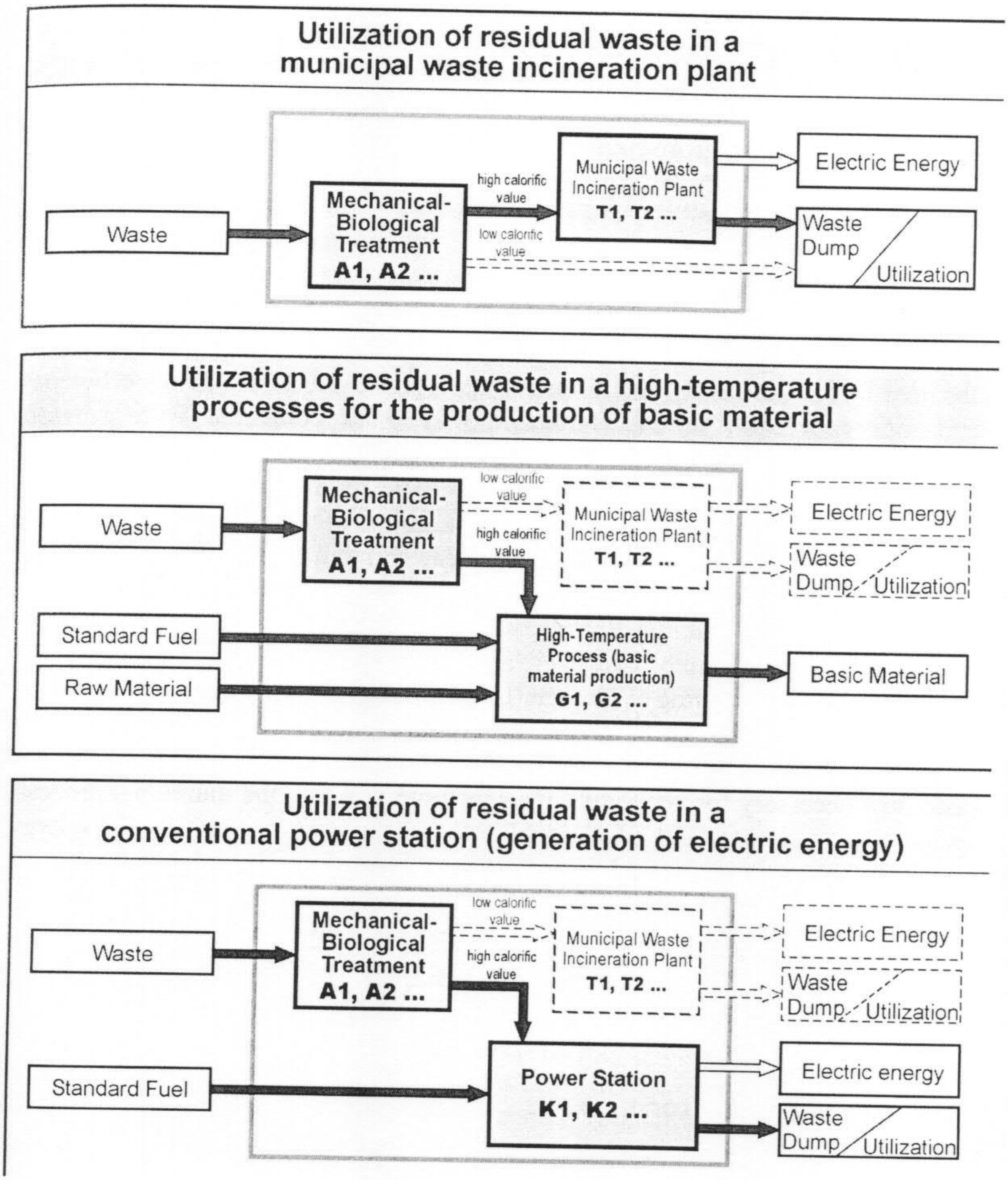
Fig. 5.23. Energy exchange ratio E dependent upon the heating value of the substitute fuel [35] (explained in the text)

Without additional measures for heat recovery, an increase in the specific energy expenditure is generally to be expected when substituting primary fuel with low heating value fuels. In [105], the practical experience from the substitution of heating oil ($h_n \approx 40$ MJ/kg) by lignite coal dust ($h_n \approx 20$ MJ/kg) is reported. This shift leads to an increased flame length, an elongated sinter zone in the direction of the furnace entrance and to higher temperatures at the furnace entrance and after the preheater. Of course, the different burn-out behavior of lignite coal dust and heating oil also plays a role. All in all there was an increase in the specific energy expenditure of approx. 170 kJ/kg_{Cl}. Half of the additional expenditure is due to the increase in the flue gas volume flow and fluctuations in the grain size, and the other half to the effects of the changes in the temperature, which can also be partially expressed through a corresponding energy exchange ratio with the above-mentioned relationship.

Energy Utilization Ratio from the Comparison of the Process Chains

The increase in the specific energy consumption of a basic materials industrial process on substituting primary fuels must not necessarily reflect negatively on using substitute fuels. In the same way, the simple fact that a certain amount of primary fuel can be saved by using fuel substitution may not be sufficient argument for doing so. All processes have to be considered. First, the substitute fuel must be generated, which requires energy (electrical energy, thermal energy, primary fuel). Furthermore, those waste fractions not used to produce the substitute fuel must also be treated (waste incineration, landfill). The requirements for a cumulative analysis that considers the mass, material and energy balances have been discussed in detail elsewhere (e.g. [152, 204, 207, 243]). The procedure will be outlined here briefly. The importance of defining the balance circles is illustrated in the schematic representation in Fig. 5.24. This shows an exemplary comparison between a conventional system (ConvS), consisting of the separate individual processes, with:

- the use of residual waste from household waste in a classical waste incineration plant (AT+T1),
- a high-temperature process for the production of e.g. cement clinker (simplified representation, labeled here as process line (G1), calcination process),
- and a combined system (CombS) consisting of:
- a pretreatment (A2, A3...),
- the use of a residual waste fraction with a high heating value in the high-temperature process (G1),
- the treatment of the residual waste fraction with a low heating value in a waste incineration plant (T1) and the (virtual) conversion of the primary fuel energy saved into electricity in a conventional power plant (K1). This allows the energetic comparison of the two systems on the basis of electrical energy under the same input conditions (input equality).



Utilization of residual waste in a municipal waste incineration plant

Utilization of residual waste in a high-temperature processes for the production of basic material

Utilization of residual waste in a conventional power station (generation of electric energy)

Fig. 5.24. Comparison of a conventional and a combined waste treatment system. In the conventional system the waste was treated in a waste incineration plant. Basic materials production process with an input of primary fuel. In the combined system the waste was pretreated and the residual waste fraction with a high heating value was subsequently used in a basic materials production process and the remaining waste fraction with a low heating value could,potentially, be used of in a waste incineration plant [204].

The Effective Energy Ratio z is defined by:

$$z = \frac{\text{energy}_{\text{combined system}}}{\text{energy}_{\text{conventional system}}}$$

Based on a cumulative consideration, the use of a substitute fuel can be assessed with the help of the energy utilization ratio z. Figure 5.24 shows clearly that, even for a higher specific energy input for the materials handling process, substitute fuel implementation can prove appropriate due to the better efficiency for power generation in the (virtual) power plant compared with a waste incineration plant. The expenditure during the generation of the substitute fuel, the intended quality of the substitute fuel and the substitution ratio in the material treatment process are decisive [36]. The discussion of the energy transfer ratio clearly shows that there is no need for a linear correlation between the effective energy ratio and the fuel substitution ratio. The low heating values of the substitute fuel mean that the heating values of the fuel mixture decrease with increasing substitution ratio. However, the energy exchange ratio increases more strongly with lower heating value, i.e. more substitute fuel is then needed for a given product and the same saving of primary energy (or the generation of electricity in the imaginary power plant). This causes an increase in the residual waste flow necessary for generating the substitute fuel. For the individual process, the increase in the amount of residual waste means an increase in the energy generated. These simple considerations show that the effective energy ratio must change continuously with the substitution ratio. It should be mentioned at this point that the analyses, which assume a linear correlation between the effective energy ratio and the substitution ratio from the start, do not sufficiently reflect the energy process-engineering requirements of the fuel substitution.

5.1.4 Hydrothermal Processes

Frédéric Vogel

Hydrothermal Processing of MSW

In supercritical or near-critical fluids have emerged over the last decades as promising alternatives to gas-phase or liquid-phase processes [67, 194, 202, 214]. This section discusses the application of near-critical and supercritical water processes to the treatment of MSW for energy production and destruction of hazardous compounds. Three routes will be presented: supercritical water oxidation (SCWO), hydrothermal gasification, and hydrothermal liquefaction.

Oxidation in supercritical water (SCWO) shows substantial promise for clean and efficient decontamination of many aqueous organic wastes [32, 83, 156, 170,