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Substitution of Fuels and Raw Materials by Waste in High Temperature Processes

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1 Introduction

At present, the production of so-called substitute fuels from waste and renewable raw materials and the utilization of these fuels in high temperature production processes, for example in the steel and cement industry as well as the chemical industry, is of increasing interest [e.g. 1-9]. In addition to the energetic utilization (substitute fuel), the material utilization (the ash) can also play a role. In both cases, the boundary conditions of the production processes (performance, process temperature profile) must of course be weighed equally along with the properties of the substitute fuels, as is case with application of conventional fuels. Additional points of view must also be considered when regarding the utilization of substitute fuels, in particular the comparative evaluation (energy exchange ratio for the substitution of the regular fuel, etc.) as well as the correlation of cumulative energy and pollutant balances.

2 Substitution of fossil fuels by waste materials

Usually, replacing fuels with waste will immediately lead to the question of the influence of the waste materials on the conditions of the respective process. Especially the effects of using substitute fuels will be examined on process temperatures, flue gas amounts, noxious substances or noxious matter loads and specific energy consumption in the case of industrial furnaces or, respectively, efficiency factors in the case of energy conversion plants. From the combustion process engineering point of view a fuel is characterized by its

- chemical, mechanical, calorific and kinetic properties.

Depending on these properties the division into special fuel gases, fuel oils or coal types results.
The properties of substitute fuels must be considered in the context of the process in the same way as for regular fuels. Therefore possibilities for

- process optimization and energy recovering

have to be examined. For a total consideration of course

- the material-, mass- and energy balances of the overall process chain must be investigated.

For the evaluation of the chemical, mechanical and kinetic properties one is dependent on empirical results and experiences. The influence of calorific properties however can be described with the help of simplified but for the praxis reliable mathematical models. Further considerations concerning process optimization and heat recovery can be connected by balancing the combustion process or the industrial kiln. It follows from this considerations that among others the calorific properties are an important criteria for the evaluation of substitute fuels. This will be reflected as follows.
It is well known that the flue gas loss of a given fuel is higher, the higher the amount of flue gas in relation to the net calorific value or the higher the flue gas temperature. The increase of flue gas loss means less fuel energy can be utilized for the process, the specific energy expenditure rises. Less apparent is the influence of the calorific combustion temperature on process conditions. For discussing this question, we examine one section of a continuous industrial furnace and – for the time being to explain the principle – for reasons of simplification liken it to a continuously stirred reactor element (CSR) (Fig. 1A, left). The supplied energy results from the conversion of fuel with air taking into account air and fuel preheating. For the time being, the basic considerations disregard the influence of a thermal dissociation balance and the theoretical combustion temperature ϑ_{th} that is determined accordingly. Thus, the calorific combustion temperature ϑ_{cal} can be used for obtaining the gas enthalpy flow. In an ideally mixed kiln chamber (CSR) this enthalpy flow effects a heat flow $\dot{Q}_{CSR}$ to the load with the constant surface temperature ϑ_{S1} and the temperature of the gas in the stirred reactor element settles at a constant temperature that equals the exit temperature ϑ_{G1}. From that, assuming adiabatic conditions, follows generally ($\vartheta_{S1} \equiv \vartheta_S$, $\vartheta_{G1} \equiv \vartheta_G$):

$$\Delta\dot{H}_G = \dot{Q}_{CSR} \quad \text{with} \tag{2.1}$$

$$\Delta\dot{H}_G = \dot{m}_G \cdot c_{G,calG} \cdot \left(\vartheta_{cal} - \vartheta_G\right) \quad \text{and} \tag{2.2}$$

$$\dot{Q}_{CSR} = \alpha_{\alpha\varepsilon} \cdot A_S \cdot \left(\vartheta_G - \vartheta_S\right) \tag{2.3}$$

where in equation (2.3) the heat transfer coefficient $\alpha_{\alpha\varepsilon}$ includes convection and radiation and A_S denotes the surface of the load. When replacing the primary fuel (PF) with the substitute fuel (SF), the demand exists that the load temperature ϑ_S and the kiln output, i.e. the exchanged heat flow $\dot{Q}$, remain unchanged:

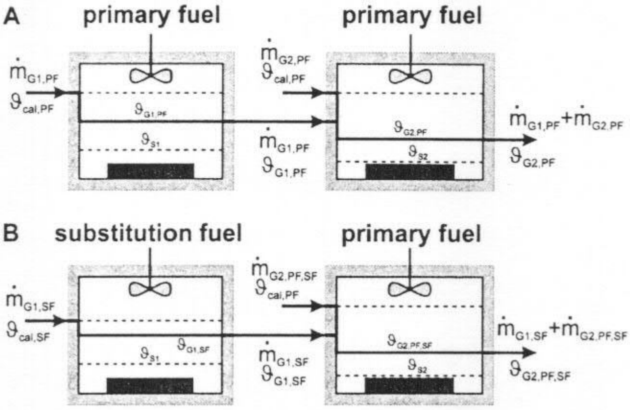

Fig. 1: Heat transfer in industrial furnaces; model idea continuously stirred reactor elements.

$$\dot{Q}_{PF} = \dot{Q}_{SF} \tag{2.4}$$

immediately yielding:

$$\Delta\dot{H}_{G,PF} = \Delta\dot{H}_{G,SF} \tag{2.5}$$

In introducing the energy exchange ratio E:

$$E = \frac{\dot{m}_{SF} \cdot h_{n,SF}}{\dot{m}_{PF} \cdot h_{n,PF}} \tag{2.6}$$

which, from an energetic point of view, expresses the value of a substitute fuel in relation to the primary fuel. Further detailed the energy exchange ratio for a continuously stirred reactor reads:

$$E_{CSR} = \frac{\left(1 + \lambda_{PF} \cdot l_{min,PF}\right) \cdot \dfrac{c_{G,PF,calG1} \cdot \left(\vartheta_{cal,PF} - \vartheta_{G1,PF}\right)}{h_{n,PF}}}{\left(1 + \lambda_{SF} \cdot l_{min,SF}\right) \cdot \dfrac{c_{G,SF,calG1} \cdot \left(\vartheta_{cal,SF} - \vartheta_{G1,SF}\right)}{h_{n,SF}}} \tag{2.7}$$

During the following examinations we assume that the conditions of heat exchange $\left(\alpha_{\alpha\varepsilon} \cdot A_S\right)$ are not influenced by the substitution (static examination). The influence of changed conditions of heat transfer is separately dealt with in an advanced step [10]. From the static examination assumed for the time being follows:

$$\vartheta_{G1,SF} = \vartheta_{G1,PF} \tag{2.8}$$

Fig. 2 shows $E_{CSR,\vartheta}$ according to equation (2.7) over a required gas temperature ϑ_G for the case of replacing a primary fuel that has a calorific value of $h_{n,PF}$ = 30 MJ/kg with a substitute fuel with $h_{n,SF}$ = 11, 15, 35 and 45 MJ/kg. The energy exchange ratio increases, the higher the required balancing temperature and the lower the calorific value of the substitute fuel as compared to the primary fuel (curves 1 to 4 in Fig. 2). Conversely, in the case of the substitute fuel having a higher calorific value than the primary fuel, the energy exchange ratio assumes values less than one (curves 5 to 8). This, for example, is the case when replacing coal with high calorific plastic wastes in the primary firing of the clinker burning process (cf. Fig. 4). When comparing the energy exchange ratios in Fig. 2 for a given substitute fuel with and without air preheating, the significance of heat recovery (e.g. recovery of heat from the load in the grate cooling-clinker burning process) becomes evident. In the case of a substitute fuel with $h_{n,SF}$ = 11 MJ/kg (curves 1 and 3), gas temperatures ϑ_G > 1700 °C can only be achieved with appropriate preheating of air.

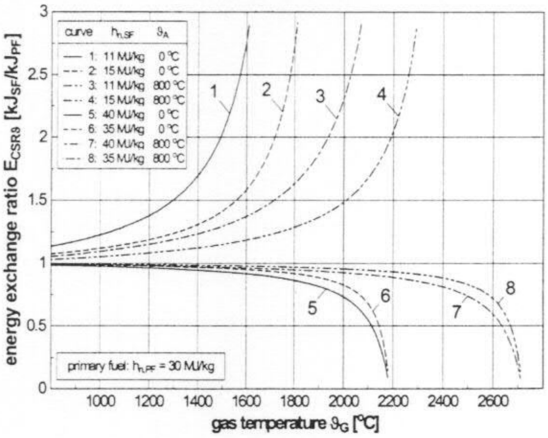

Fig. 2: Energy exchange ratio by static observation in dependence of the gas temperature for different substitution cases.

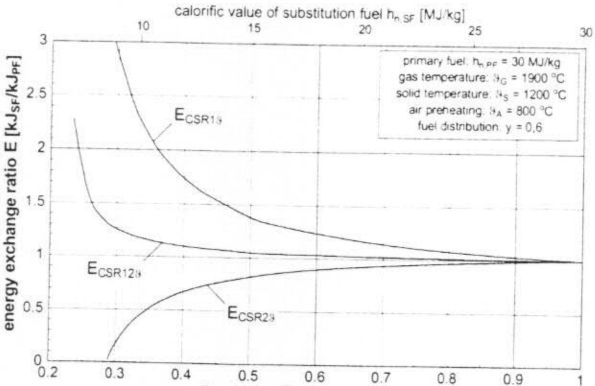

Fig. 3: *Energy exchange ratio by static observation in dependence of the ratio of calorific values for two stage fuel feed.*

In the first step discussed above, only one section of an industrial furnace was examined under simplified conditions (just one continuously stirred reactor element) with regard to the energy exchange ratio of fuel substitution. However, as mentioned above, the evaluation of a fuel depends not alone on the kind of fuel but also on process management and heat recovery. Therefore, the amount of additional energy expenditure in the case of fuel substitution, as opposed to primary fuel use, required primarily for attaining high process temperatures, e.g. in a burning or calcining process, is not necessarily "lost". For example, with a two-fold staging of the energy input along the treatment path (primary and secondary firing with the clinker burning process), a balance schema as in Fig. 1 can be derived, again making use of the aforementioned simplified model of continuously stirred reactor elements for the first and second stage and assuming static examination ($\vartheta_{G,PF} = \vartheta_{G,SF}$). The single Fig. 1A present the first and second stage of the original process, i.e. with primary fuel supply in the respective stages ($\dot{m}_{PF1}$ and $\dot{m}_{PF2}$). This process is now compared to a case in which, in the first stage, the primary fuel supply is replaced with substitute fuel $\dot{m}_{SF1}$ according to the exchange ratio $E_{CSR,\vartheta}$ mentioned above (Fig. 1B).

As in the case of the previous example, with a primary fuel that has $h_{n,PF}$ = 30 MJ/kg, a balancing temperature ϑ_{G1} = 1900 °C and air preheated to ϑ_A = 800 °C, Fig. 3 presents the energy exchange ratio $E_{CSR1,\vartheta}$ over $h_{n,SF}$. Furthermore, for a fixed balancing temperature ϑ_{G2} = 1200 °C, the curve for $E_{CSR2,\vartheta}$ is included, the course of which, due to the savings achieved in the second continuously stirred reactor, assumes values less than 1 in this presented substitution case. Notwithstanding the fact that $E_{CSR12,\vartheta}$ is greater than 1, due to the possibility of a staged fuel supply, it is still significantly smaller than $E_{CSR1,\vartheta}$.

3 Effects of Substitution on Process Management (Example)

With the above acquired and examined findings, greatly simplified with regard to some general aspects of fuel substitution, the following examples are discussed concerning the impact of fuel substitution on the respective process management clinker burning process in the cement industry.

The underlying presumption in the following considerations is that the substitute fuels, based on their material properties, are principally suitable for substitution both with regard to product quality as well as to emission of pollutants. In Germany, cement clinker is produced mainly according to the so-called dry method. As seen in Fig. 4, the plant consists of the main components preheater, calcinator (combustion chamber), rotary kiln and clinker cooler (grate). Fuel is supplied through three inlets: the primary firing (kiln exit, I in Fig. 4), the supplemental firing at the kiln entrance (II) and the secondary firing (calcinator, III). In principle, substitute fuel can be supplied at all three inlets, however, the specific boundary conditions need to be adhered to.

In the combustion zone, the primary firing for the burning of the clinker needs to achieve approximate maximum load temperatures around $\vartheta_S \approx 1500$ °C or gas temperatures $\vartheta_G \approx 1900$ °C. For example, a question could be, to what extent coal supplied as primary fuel with $h_{n,PF}$ = 30 MJ/kg can be replaced with a substitute fuel gained from adequately pre-treated waste with $h_{n,SF}$ = 15 MJ/kg. In this case, the energy exchange ratio, for the time being, only needs to be examined for the first stage. With the simplified relations derived in chapter 2, Fig. 3 states $E_{CSR,\vartheta} \approx 1.3$ for this case. This entails a 2.6-fold amount of fuel and about 1.5-fold amount of flue gas when using the substitute fuel as opposed to the primary fuel. These circumstances prohibit a complete substitution, amongst other things with regard to aspects concerning the plant such as supply units, gas velocities in the rotary kiln, sweeping away of particles of the load by the gas flow etc. Therefore, with regard to justifiable changes of the boundary conditions, only amounts of 30 to 50 mass-% could be replaced in this case. With a primary fuel of h_n = 30 MJ/kg, a 50 % exchange with substitute fuel would result in a new mean calorific value of $h_{n,SF}$ = 22.5 MJ/kg. Thus, the energy exchange ratio amounts to a mere $E_1 \approx 1.1$.

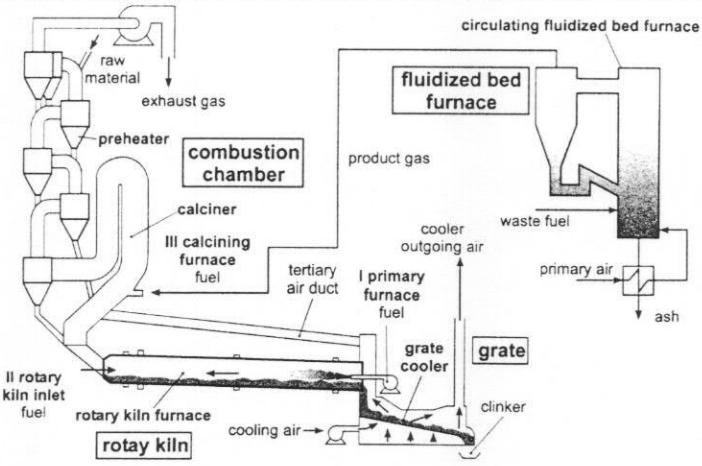

Fig. 4: *Schematic presentation of the cement process in combination with a fluidized bed furnace.*

In the second step, the effects need to be investigated of the substitution in the primary firing on the secondary firing that is still being operated on coal. As previously mentioned, this staged manner of supplying fuel enables a part of the additional energy expenditure, due to substitution and required for the incineration process, to be utilized in the succeeding sections. With cement rotary kiln plants, the share of fuel in the second firing commonly ranges at about $y = 0.6$. Due to the limitation of the substitution rate in the first stage, the consequences for the overall process are low. For the example observed here, a total energy exchange ratio near 1 is obtained. Therefore, depending on the process management, a smaller overall energy exchange ratio can be obtained. Beyond the scope of the simplified relations presented here the determination of this ratio, however, requires suitable process models and practical research. As a rule, without additional measures for heat recovery, replacement with a substitute fuel of lower calorific value entails an increase of the specific energy expenditure. For example, [11] reports of practical experience with a change-over of an incineration process from fuel oil ($h_n \approx 40$ MJ/kg) to lignite dust ($h_n \approx 20$ MJ/kg). Amongst other things, this modification lead to a greater flame length, a shift of the sintering zone toward the kiln entrance and to a temperature rise at the kiln entrance as well as behind the preheater. Naturally, here the differing burnout behavior of lignite dust and fuel oil plays a part. Altogether, the outcome was an increase of specific energy expenditure by about 170 kJ/kg_{cl}. The additional expenditure is attributed in equal parts to the increase of the flue gas mass flow on the one hand and to the fluctuation of grain sizes – and its respective effect on the course of temperature – on the other hand.

Concerning the secondary firing, due to lower temperatures compared to the primary firing, the energy exchange ratio in relation to the temperature is of less significance. According to Fig. 2, required gas temperatures of $\vartheta_G \approx 1200$ °C entail energy exchange ratios only slightly greater than one, even when the calorific value is lowered from 30 MJ/kg to 15 MJ/kg. Of significance is, when applying substitution to the secondary firing, the quality of the fuel with regard to the specific flue gas volume and the burnout. Larger-size particles such as tyre cuttings fall into the rotary kiln's entrance area where they cause a rise in temperature. Through incomplete combustion, the process of incineration could extend into the preheating zone. Concerning this, Fig. 5 displays results from practical research [12]. Amongst other things, the figure shows that, when applying tyre cuttings, the increase of secondary fuel energy in relation to the clinker mass causes the gas temperatures to rise at the kiln entrance. This temperature rise in turn effects an increased alkaline salt vaporization in the rotary kiln. Conversely, when using a fuel with relatively good burnout properties, the conversion takes place mainly in the calcinators gas rising duct and a reduction of alkaline salt recirculation can be expected. In the present example, an increase of the secondary fuel share through input of coal dust causes, due to a reduction in the primary fuel share, a fall in gas temperature at the kilns entrance, thereby reducing the release of K_2O. A reduced amount of alkalines in the cycle finally leads to a smaller specific energy expenditure. Here, however, a complete burnout of the secondary fuel in the calcinator is presumed.

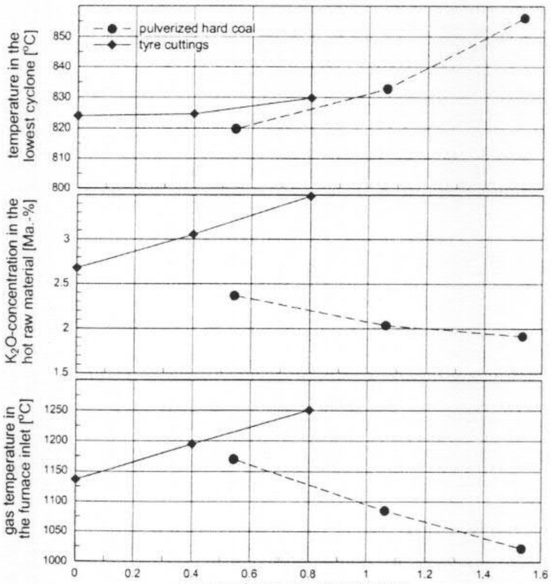

Fig. 5: *Influence of secondary fuel feeding on the process behavior.*

4 Nomenclature

Symbols

α	heat transfer coefficient
Δ	difference
λ	stoichiometric ratio; air ratio
ϑ	temperature [°C]
A	area; exchange factor
c	specific heat capacity
CSR	continuously stirred reactor
E	energy exchange ratio
h	specific enthalpy
H	enthalpy
l	specific air requirement
m	mass
Q	heat
y	stage 2 fuel mass in relation to total fuel mass; fuel distribution

Indices (in superscript)

·	flow

Indices (in subscript)

1, 2	stages 1, 2
α	convection
ε	radiation
ϑ	temperature
A	air
cal	calorific
cl	clinker
CSR	continuously stirred reactor
G	flue gas
min	minimum
n	net (calorific value)
PF	primary fuel
S	solid
SF	substitute fuel
th	theoretical
	constant gas temperature (static examination)

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