MATHEMATICAL MODELLING OF THE CEMENT CLINKER BURNING PROCESS

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Summary

The mathematical model developed at the “Forschungsinstitut der Zementindustrie“ can be used for calculating the clinker burning process from when kiln meal is fed into a cyclone preheater to discharge of the clinker from the cooler. It is based on energy and material balances, and consists of individual models for the plant components, namely preheater, calciner, gas off-take (bypass), rotary kiln and grate cooler. The models are linked mathematically to one another and make it possible to calculate a steady-state condition for the entire plant. Aim of the work is use the calculations to optimise the clinker burning process.

Introduction

Mathematical modelling of the respective processes is already far advanced in many branches of industry. However, so far only very few models exist for the cement clinker burning process. An important reason for this is the complexity of the heat transfer, over which comparatively little is known and which takes place simultaneously with chemical, physical and mineralogical reactions.

Nevertheless, many of the phenomena relevant to the clinker burning process have been investigated individually in detail. These include, for example, calcination, clinker phase formation, combustion of fuels and heat transfer in packed beds. These processes are now sufficiently well understood to be able to develop mathematical expressions and compare their results with practical measurements. They have been combined in this work to form a complete model so that the interactions between plant sections and individual reactions can also be taken into account [1–5].

The model describes the clinker burning process from the kiln meal feed to the discharge of clinker from the cooler, and consists of individual models for preheater, calciner, gas off-take (bypass), rotary kiln and grate cooler. The models are linked mathematically to one another through the flows of kiln feed, gas and dust, and make it possible to calculate a steady-state condition for the entire kiln plant. An important aim of the work is use the calculations to optimise the clinker burning process.

Calculation for the complete plant

The model presented here for the complete plant is based on the models of the plant sections for which the operating condition is determined using an iterative calculation procedure. For this, the initially estimated solutions of the balance equations for mass and energy are improved with the aid of similar calculation steps until the required accuracy is achieved, Table 1. The calculation of the steady-state conditions for the complete plant builds on this procedure by combining the solution steps for the plant sections with one another and exchanging the results between the sections at their interfaces, Figure 1. On a normal commercial PC (Pentium III, 800 MHz, Windows NT) a complete calculation requires about 20 minutes.

Balance area	Energy balance [W]	Mass balance [g/h]
Cyclone	1	10
Preheater	200	300
Calciner	100	100
Kiln	100	500
Cooler	100	0.1
Complete plant	500	1000

Table 1: Accuracy of balances

The calculations were performed for the four-stage preheater plant shown in Figure 1, for which an energy balance is available. All the data on the marginal conditions for the process were taken from the test report as long as appropriate measurements had been carried out. This included, for example, the information on the input materials and all the adjustments undertaken by the operating personnel. Parameters which were not available were estimated on the basis of literature information and empirical values from operational measurements.

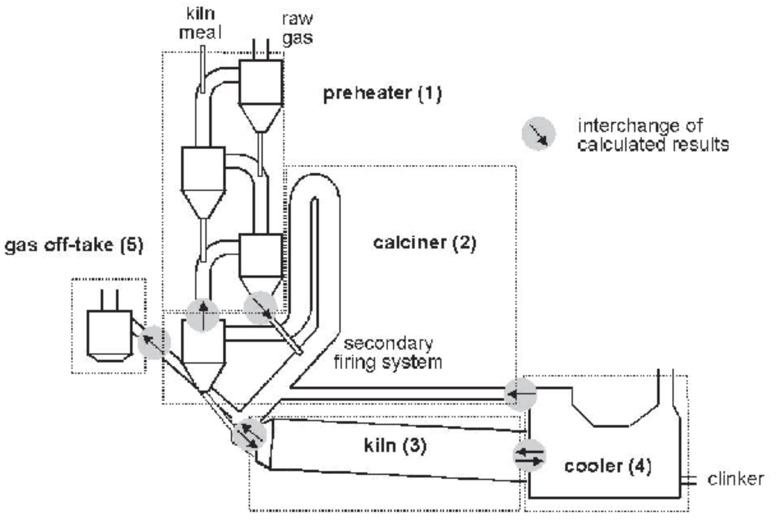

Figure 1: Balance areas and calculation sequence for the plant sections

A comparison between measured and calculated values shows high agreement, Table 2. It is emphasised, that the calculations are exclusively based on commonly agreed fundamentals of process engineering, heat transfer and material science. Every model parameter has a scientific or technical meaning and, in particular, there are no parameters devoted to the fitting of measurements with model results.

	Measurement	Model
Specific energy requirement	3231 kJ/kg$_{cli}$	3315 kJ/kg$_{cli}$
Temperature of the raw gas	350 °C	362 °C
Temperature of the clinker	177 °C	177 °C
Cooling area efficiency	70,6 %	72,0 %
C_3S content of the clinker	53 – 64 %	61.1 %
Dust content of the raw gas	70 g/m³ dry	75 g/m³ dry

Table 2: Comparison of measured and calculated values for a four-stage preheater plant with calciner and bypass

Calculation studies

Based on such a reference condition it is possible to apply changes to the model in order to investigate on the overall result. For this, the results of the reference condition are compared to those which were obtained under changed conditions. It must be borne in mind that clinker with a quality comparable with that of the reference condition must still be produced. This was ensured by assuming in the calculations that the same kiln feed temperature as in the reference condition must still be achieved in the sintering zone under the changed conditions. In the studies this temperature was therefore adjusted to match the temperature in the reference condition with the aid of the fuel feed to the primary firing system. The additional use or saving of fuel therefore permits an initial estimate to be made of the effects of the parameter change on the energy in the complete process.

Additional correction measures – particularly optimisation of the operating condition – were dispensed with so as not to mask the effects of the parameter change. The calculations presented here should therefore not be evaluated as being the result of plant optimisation to achieve the lowest possible specific energy requirement. This requires further calculations in which specific changes are also made to other settings. Practical implementation would also have to be checked in each individual case in order to avoid plant stoppages or damage.

Dust collection in the preheater

The changes in the recirculating dust systems in the preheater have a comparatively significant effect on the specific energy consumption of the plant. A deterioration in the collecting efficiency of the two top cyclones by 5 % in each case to 90 % and 85 % respectively and in the third cyclone from 70 % to 60 % lead to an additional consumption of 186 kJ/kg$_{cli}$ (+ 5,9 %). A substantial proportion of this is accounted for by the losses with the raw gas (103 kJ/kg$_{cli}$) and the raw gas dust (58 kJ/kg$_{cli}$). The slightly increased wall heat losses contrast with somewhat lower losses through cooler exhaust air and clinker, Figure 2.

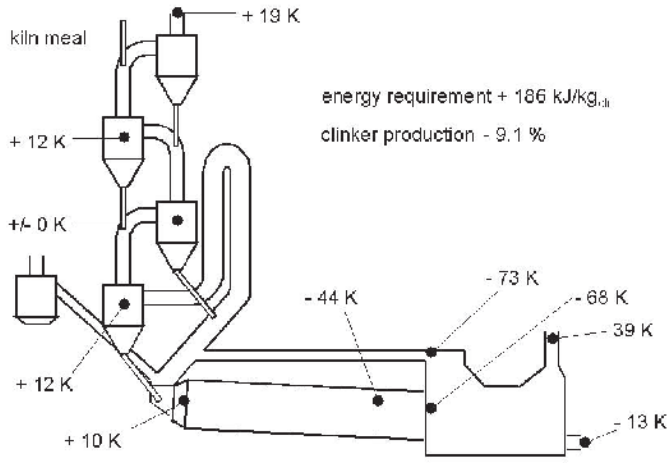

Figure 2: Effect of low dust collection efficiencies in the preheater

Increased dust losses reduce the clinker production by 9.1 % and in this way also affect the temperature profile in the plant. The cooling air in the cooler is distributed to a smaller mass of clinker so that this is cooled to a greater extent. At the same time there is a drop in the temperatures of the secondary and tertiary air and in the temperature in the sintering zone (- 44 K). This results in a deterioration of the heat transfer from the gas to the kiln feed, and the gas temperature at the kiln inlet rises by 10 K. Increased recirculating dust systems lead to the establishment of higher temperatures than in the reference condition, especially in the upper part of the preheater. Similarly, an improvement in the collection efficiency of the top cyclone from 95 % to 98 % with otherwise unchanged collection efficiencies produces a saving of 55 kJ/kg$_{cli}$ (-1.7 %) and an increase of 4.2 % in the clinker production.

Particle size distribution of the clinker

Fine-grained clinker is considerably easier to cool than coarse-grained clinker. The smallest particles (diameter 1 mm) leave the cooler with a temperature of 66 °C, but the temperature in the largest particles (diameter 100 mm) is still 679 °C, Figure 3. This difference between the large and small clinker particles is explained by the relationship between volume and surface area. The heat stored in a clinker particle is dependent on the volume while the heat exchange with the surroundings takes place through the surface. With increasing diameter, the volume of the particle increases to the power of three, i. e. more rapidly then its surface area which increases to the power of two. As a consequence, the heat which the particle can store grows more strongly then its ability to release heat to the surroundings.

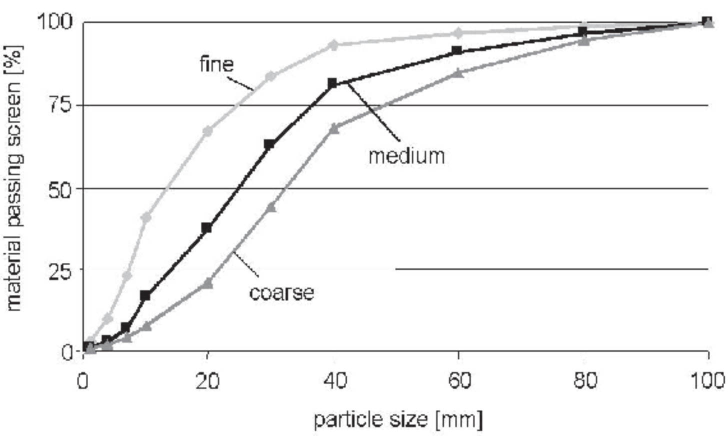

Figure 3: Particle size distribution of the clinker

The change from normal to coarse-grained or fine-grained clinker (compare particle size distribution in Figure 4) has significant effects on the cooling area efficiency, which for fine-grained clinker is calculated very high (81.2 %). The change has a direct influence on the specific energy consumption of the plant and in the case of the fine-grained clinker gives a saving of 88 kJ/kg$_{cli}$ (2.8 %) and for coarse-grained clinker results in an additional consumption of 68 kJ/kg$_{cli}$

(2.2 %). In both cases this is primarily attributable to changed energy losses through the clinker and cooler exhaust air. At the same time the temperature profile of the kiln, preheater and calciner is raised for fine-grained clinker and lowered for coarse-grained clinker.

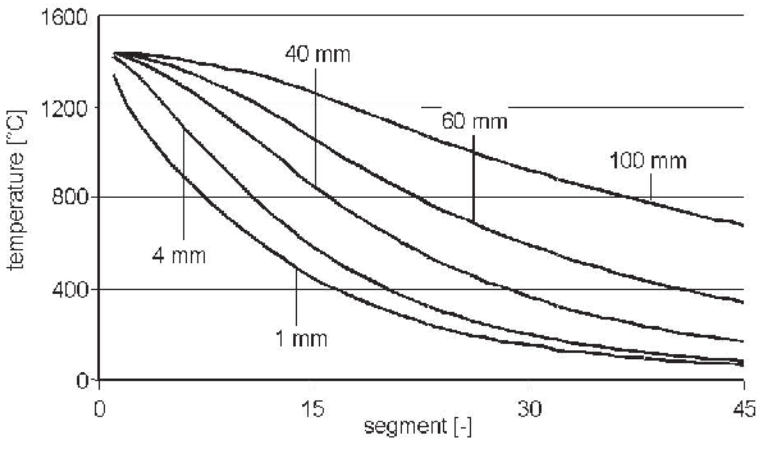

Figure 4: Calculated temperature curves for some particle fractions

Clinker quality

Material influencing factors were investigated by assuming differing levels of lime in the kiln meal. In the reference condition the lime standard of the mixture of kiln meal and fuel ash was 93.6. This mixture was changed in two calculations so that the lime standards were 100.0 and 86.0 respectively for the same silica ratio, alumina ratio and silicic acid modulus.

Burning the lime rich clinker theoretically increases the specific energy requirement by 82 kJ/kg_{cli} as a result of the chemical reactions. This is due primarily to the additional energy for calcining the $CaCO_3$, which is partially offset by the heat recovery during the clinker phase formation. The model also takes account of the formation of intermediate phases which are not present in the burnt clinker. The percentage of C_3S increases from 61.1 % to 67.7 % (Table 3) at the expense of the percentage of C_2S which decreases from 16.6 % to 10.6 %. At the same time the clinker production is reduced by 1.0 percent. The use of the low-lime kiln feed mix has the opposite effect; with a lime standard of 86.0 the specific energy requirement falls by 85 kJ/kg_{cli} compared with the reference condition and leads to a C_3S content of only 51.3 %. At the same time the clinker production rises by 0.9 %.

	Low-lime clinker Lime standard 86,0	Reference clinker Lime standard 93,6	Lime-rich clinker Lime standard 100
C_3S	51,3	61,1	67,7
C_2S	26,2	16,6	10,6
C_3A	9,4	10,8	11,2
C_4AF	3,9	4,6	4,8
CaO	0,2	0,7	1.8

Table 3: Calculated clinker phases in %

In practice the change in lime standard is generally linked with a change in process temperatures. With the simultaneous assumption of a low-lime kiln feed mix and a sintering zone temperature which is reduced by 80 K there is theoretically a reduction in the specific energy requirement by 183 kJ/kg_{cli}. This is made up primarily of savings in the chemical reactions (87 kJ/kg_{cli}), raw gas (34 kJ/kg_{cli}), cooler exhaust air (24 kJ/kg_{cli}) and wall heat (23 kJ/kg_{cli}). It should be mentioned that in order to save fuel energy there have been repeated attempts to produce low-lime "belite clinker" and adjust the quality of the cement by grinding to a higher fineness. However, the success of this procedure is debatable because of the greater energy expenditure for grinding the clinker.

Summary and outlook

The joint model for the clinker burning process is based on energy and material balances and consists of individual models for the plant components, namely preheater, calciner, bypass, rotary kiln and grate cooler. The modular design allows, to adapt it comparatively easy and flexible to different cement plants. By taking into account material as well as process engineering and plant processes the clinker burning process can be calculated close to practice. The results are in agreement with the present understanding of the process. However, they can only be verified in individual cases as it is not yet possible to make sufficiently accurate measurements in all areas of the kiln plant. Improvements to the model are needed, especially with respect to the material processes. From the energy point of view these processes can be comparable with plant and process engineering factors and must therefore not be neglected in the energy and mass balances. They are also important with respect to clinker quality and environmental protection.

Even in its present state the model can be used to carry out theoretical investigations of changes in a plant in advance. With a procedure analogous to that used in this work the changes can be assessed by comparison of the calculation for a reference condition with the calculated results for the modified plant. At present this primarily concerns energy and material questions such as a changed mode of operation, the use of secondary materials, and plant modifications. This will be extended in the future to cover emissions as part of a research project.

References

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