Camera Based Optimization of Multi-Fuel Burners for the Use of Substitute Fuels in the Cement Industry

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Cement plants use a huge amount of fossil energy. The use of Solid Recovered Fuels (SRF) reduces fossil fuels and energy cost. However, these SRF negatively affect process and product quality. The optimization of multi-fuel-burners for the use of SRF is highly relevant for the cement industry. More and more so-called multi-fuel burners are employed in thermal processes like the cement industry. In addition to regular fuels such as coal and oil, multi-fuel burners allow for the burning of low-rank fuels of biogenic and

MBT and SRF

fossil origin. The usage of these low-rank fuels enables a cost-saving and CO_2-reduced energy generation for various applications from the chemical industry (cement) to power plants. The varying fuel compositions associated with the use of widely varying low-rank fuel compositions require an appropriate process control for the permanent adjustment of burner parameters to support an optimal incineration. Such a process control demands a detailed knowledge of the current process state – the combustion behavior – which cannot be acquired adequately with existing measurement systems. The use of special spectral infrared camera systems in conjunction with powerful image processing systems opens a new perspective to derive new and innovative parameters useable for the process optimization. Thus, there is the possibility to analyze different fuel combinations dissolved in time and place in different spectral ranges and in real-time and therefrom calculate characteristic image-based parameters. These parameters describe the current combustion state in detail and allow optimizing the burner control. In addition, abrasion-caused burner shifts and changes in the fuel supply chain are detectable in real-time in order to initiate appropriate countermeasures.

1. Background information: Why camera based optimization of multi-fuel burners for the use of substitute fuels in the cement industry are reasonable

Modern multi-fuel burners enable a detailed adjustment of different burning parameters for the use of SRF. Therefore, the relevant parameters must be determined in a robust and reliable way. In order to detect the burning behavior of SRFs online and in real time, infrared (IR) cameras can be applied. Under manageable conditions, the derived IR-camera-based parameters can be used for optimizing control.

Within the Comfeb project, the ci-tec company and the Karlsruhe Institute of Technology collaborate to develop such a control system for multi-fuel burners which enables the usage of SRF in rotary kilns for cement production. Herein, an infrared camera is installed inside the rotary kiln to acquire images of the burning process. These data are processed by image-based algorithm modules which are part of the control system. A further module of the control system calculates indicators of the burning process based on the IR-data and controls settings of the multi-fuel burner. Parameters characterizing the behavior of alternative fuel are for example detection of the fuel streak line at the rotary kiln head. For example, the characteristics of the streak line can be changed according to settings of the combustion air or pneumo deflector (e.g. [6], [4]).

In sum the new technology, illustrated in this article, enables operators of cements plants to increase the usage of solid substitute fuels, since the developed systems monitors the burning process via an IR-camera and is coupled with the control system of a rotary kiln. The negative effect of the SRFs on the product quality is minimized by the optimization of the burning process through the embedded real-time control of burner parameters. The control tool developed within the Comfeb Project is currently validated at an industrial plant to gain optimal operation of multi-fuel burners.

2. Thermal processes in the cement industry and the requirement of a control system in the context of multi-fuel burner use

In thermal processes, such as power plants and process plants, in particular the cement industry, more and more so-called multi-fuel burners are employed. In addition to regular fuels such as coal and oil, multi-fuel burners allow for the burning of low-rank fuels of biogenic and fossil origin. The usage of these low-rank fuels ensures a cost-saving and CO_2-reduced energy generation for various applications from the chemical industry (cement) to power plants.

However, these fuels have greater variations in material properties such as in the particle size distribution, the calorific value or the moisture and can therefore lead to a transient combustion behavior with unfavorable pollutant formation and energy efficiency or even to the failure of the burner ([4], [3]). Furthermore, abrasion and contamination are strongly dependent on the fuel composition and affect the combustion process accordingly.

There is also the requirement for fast adaptation ability of the burner operation at current load demands for modern processes and decentralized power plant concepts. Both factors – highly varying fuel composition with changes in properties as well as load requirements – demand an appropriate process control for (a) the permanent adjustment of burner parameters to the fuel and (b) load conditions. Regarding (a) this includes e.g. fuel flow rate and composition, stoichiometry and twist, which can be regulated to a various degree.

The objectives of such a burner control is, generally speaking, the optimization of the burning processes. In detail, the presented approach of a control systems focuses on the maximization of energy efficiency with simultaneous reduction/avoidance of combustion pollutants and the increase of system life period as well as reliability when using low-grade fuels. Additionally, in locally distributed processes, the specific and stable distribution of the energy input is essential. The length of the flame and the particle trajectory are to be identified and set. However, such a process control requires the detailed knowledge of the current process state.

One prerequisite for monitoring the process state is the detailed measurement of the actual combustion situation. The present situation in this case is not a satisfactory and reliable solution: the reliability of the conventional measurement systems such as pyrometers, thermocouples and exhaust gas sensors, etc. is regarded as low in context of fully mapping the processes in a rotary kiln. Thus, for current burner systems with conventional sensors and control, the use of low-rank fuels is either not possible or only accomplishable with insufficient unstable energy yield. The use of new camera systems in conjunction with powerful innovative image processing systems opens an alternative perspective for the process optimization. With this conjunction of hard- and software the path is opened to analyze different fuel combinations dissolved in time and place in different spectral ranges, in real-time and therefrom determine new image-based parameters. These parameters describe almost in full context the current combustion state in detail and hence allow optimizing the burner control.

3. The Comfeb project: A brief introduction of the objectives

The objective of the Comfeb project is assembled by two combining parts: The first part consists of the development of a process-specific basis for an optical measurement system consisting of (a) a camera system, (b) an image acquisition module and (c) an image processing module which provides parameters for a control optimization of multi-fuel burner. The second part involves the prototypical demonstration of the feasibility at a real, industrial plant in regard to the utilization of the extracted parameters for the optimization of the process control. A thus optimized burner control would ensure an improved use of energy (efficiency) combined with lower emissions. By using such a system, existing old systems could be updated and simultaneously optimized to a considerable extent. Moreover, new plants are not excluded and could be equipped with the Comfeb system.

The development of such a new measurement system was a scientific and pre-competitive task with certain risks in image acquisition, fault clean-up, image analysis, calculation of the required parameters and their usage in the process control. As the current installation shows measurably success, finally, the realization of a product with a high innovation and market potential for a new market segment will be successful completed. Emphasizing this, previous preliminary scientific studies with different camera systems at several plants in the cement industry have confirmed the basic approach of the project.

4. Significant characteristics of multi-fuel burners in an overview

In the field of industrial combustion processes the number of multi-fuel burners has increased significantly during the last years. These multi-fuel burners can use alternative fuels like plastic, tire chips or animal meal in arbitrary high fractions besides fossil primary fuels such as brown coal.

Figure 1:

Example of a multi-fuel burner from the company Unitherm Cemcon

Source: Cemcon, U.: M.A.S. Kiln Burner – UNICAL Calciner Burner. 2015

Due to declining availability of fossil fuels, the use of these low-cost, low-ranked and in large quantities available alternative fuels provides a great savings potential. At the same time the increased use of alternative fuels can not only reduce costs but also reduce emissions [6]. Figure 1 illustrates an example of such a multi-fuel burner that includes two supply channels for fuel and combustion air.

Figure 2 shows schematically the structure of a multi-fuel burner which is used in the application of this work. The primary fossil fuel is added by the co-axially arranged coal channel. For alternative fuel two supply channels are available. During the measurements at the cement kiln in the application of this work, a mixture of plastic and tire chips are fed to channel 1 and animal meal to channel 2. The coaxially arranged swirl air channel influences the flame shape. Thus, increasing the swirl leads to shortening the expanded flame, and vice versa. Another control factor of changing the flame shape is the pressure of the swirl air, more precisely the primary air. The exit angle of the alternative fuel – the pneumo deflector – is located at the end of the alternative fuel channel 1 (Figure 2, middle). The pressure of a vertical air flow is directly affected by this exit angle. Increasing the pressure simultaneously increases the exit angle as well as the diversification of the fuel. The rotational speed of the conveying air blower controls the initial speed of the alternative fuel of channel 1. One task of the central air pressure is to stabilize the flame. To sharpen the flame near the burner mouth, the pressure of the central air needs to be increased.

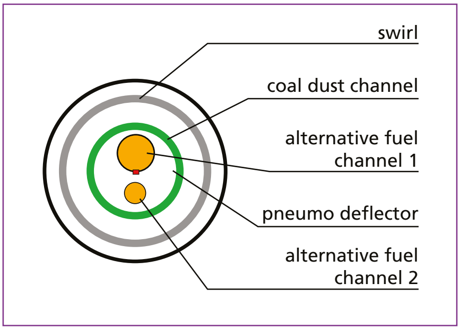

Figure 2: Schematic illustration of the front of a multi-fuel burner

5. Control optimization of multi-fuel burners based on developed image analysis methods

This section details the applied and developed image analysis methods that extract information of IR-data to oversee the current burning process state. The primary focus lies on the combustion behavior from which the demands of a reliable, robust process control system can be derived. As mentioned in the sections above, the basis image data is acquired by a new IR-camera system. This IR-camera allows to derive new, innovative parameters useable for the process optimization. Hence, different fuel combinations dissolved in time and place can be analyzed for different spectral ranges in real-time.

5.1. General workflow in image processing

In general, image processing methods are used for the automatic analysis of scenes acquired by camera systems. The employed image analysis methods in this article are new with respect to the process specific challenges (for further details [8], [6], [4]). The general workflow this article follows is depicted in Figure 3.

The basis is a camera system that ensures the visibility of the objects of interest. In this application, an IR-camera (10,6 µm). In a next step, it is necessary to improve the obtained raw images with preprocessing methods or to emphasize image content of interest, in order to facilitate the following analysis. The analysis often incorporates the segmentation of specific image regions, the extraction of gray value characteristics, or texture features. Thus, parameters are derived that allow a scene interpretation and consequently enable human intervention or automatic process control.

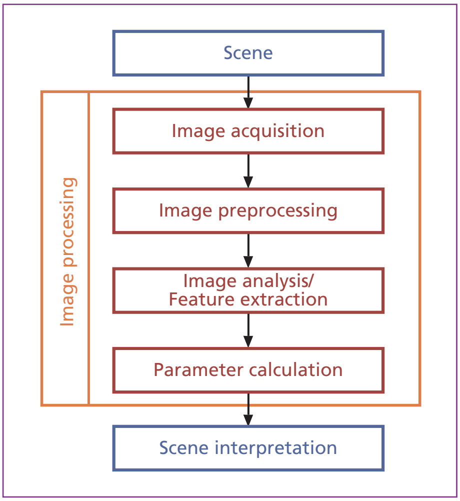

Figure 3: General workflow for scene analysis

5.2. Pre-processing

After the acquisition of image data of the scene of interest by an infrared camera system, the pre-processing prepares the raw image data for the main analysis. For the pre-processing, this article introduces three methods that were developed to support a successful detection of alternative fuel ([6], [3])

5.2.1. Evaluating the visibility of the fuel due to dust exposure

Due to dust exposure, an evaluation of the visibility of the fuel is needed, because a high dust exposure may cause a significant occlusion of fuel. Thus, homogeneous gray values in this specific part of the image are produced (Figure 4).

The introduction of a view condition parameter allows to estimate the visibility of the fuel. The parameter represents the image contrast and is calculated by the sum of the absolute values of the gradients in a region where fuel can occur. For further automatic image analysis fitting images are pre-selected by a comparison of the parameter with a threshold.

Figure 4: IR-camera images of multi-fuel burner at heavy dust exposure (poor view conditions)

5.2.2. Determining whether the burner tip is still in the right position or whether cakings cover fractions of the fuel

To verify the correct burner position, an automatic check, if the burner tip is still in the right position or whether cakings cover fractions of the fuel, is essential. Thus, constant acquisition conditions can be guaranteed. Due to burner maintenance or after a demounting of the camera, changed burner position may occur. Hence, only a correct burner position enables an accurate estimation of predetermined regions for further evaluation and comparability. The approach used in this article is template matching of the burner tip. The templates are represented by simple contour lines of the burner tip (Figure 5, red outline) generated from varying rotation angles.

The position of the burner tip itself is represented by the exit point of the fuel at the front of the burner (Figure 5, blue cross). With constant acquisition conditions ensured, the position can be determined within a quadratic acceptance window of a few pixels. This localization of the burner tip makes sure that the recording constellation is not changed significantly.

Figure 5: Template matching for burner tip detection

5.2.3. Identify cakings in cropped image to prevent false detections

The next pre-processing method uses the output of the previous two and first crops a region of interest from the image where the fuel detection later takes place in the main analysis (Figure 6).

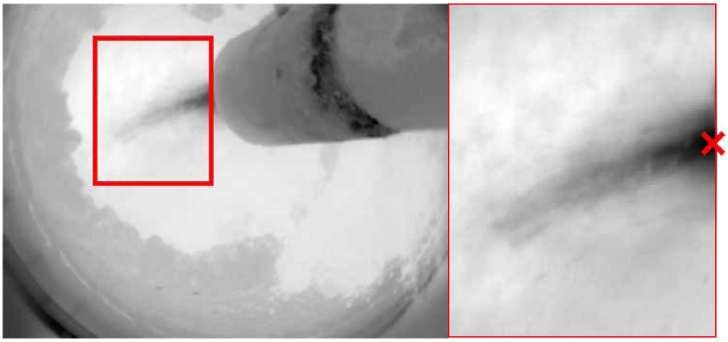

Figure 6: Cropping image to region of interest (red rectangle) for fuel detection

However, this region may contain cakings on the kiln wall caused by the rotation of the kiln, which block the view on the fuel. To prevent false detection because of the similar temperatures of cakings and fuel, a segmentation of cakings is necessary. The segmentation is based on the evaluation of the gray values at the image edge. If cakings appear, also gray value break-ins appear which are detected by minima detections. These minima are used as seed points for a subsequent region growing method which is the result of the segmentation. Figure 7 shows an example of the segmentation method.

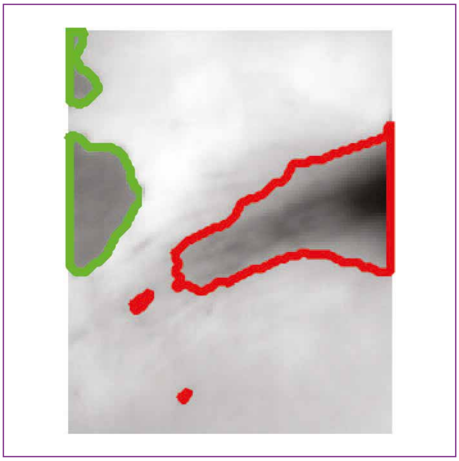

Figure 7: Result after segmentation process of cakings and fuel

5.3. Image analysis

The described pre-processing methods ensure an undisturbed detection of the alternative fuel. The main analysis of the fuel is split into two methods depending on the appearance of the fuel. Due to the concentrated input, the fuel appears very concentrated close to the burner tip. With increasing distance to the burner tip the fuel scatters and individual as well as agglomerated fuel particles can be observed. The first aspect is obtained by a low-pass filter and a column-by-column minima detection. The second one, including detection of particles and agglomerations, is done by SIFT detection. The combination of both methods leads to an estimation of the alternative fuel streak line ([6] and Figure 8).

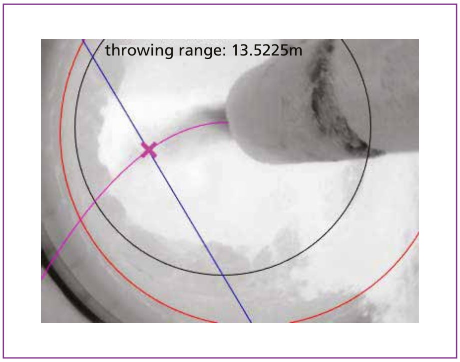

Figure 8: Estimation of the fuel streak line (purple) and calculation of throw distance

5.4. Parameter calculation

On the basis of the detected streak line, parameters are derived, which are integrated in the online monitoring of the process optimization software. For example, the throw distance of the alternative fuel (Figure 8, magenta line) can be calculated to estimate the combustion behavior and to adapt the burner settings. The angle the fuel is leaving the burner tip is another important parameter. With controlling the angle by adjusting the burner settings it can be guaranteed that the fuel is completely converted and do not negatively affect the product quality. The derived parameters guarantee the adjustment of the control and thus the optimization of the combustion behavior of the alternative fuel.

6. The *inspect pro control C* system

The developed and above described methods of (a) pre-processing IR-image data, (b) analyzing the latter and (c) calculating characteristic parameters of the combustion behavior are bundled and integrated as modules in the software system inspect pro control C (schematic link in Figure 9). Based on the IR-images pre-/processed in this system, parameters are derived and the process control of the burner settings is adapted to optimize operations. The conventional and fuzzy control implemented in the inspect core modules ensure a significant optimization relying on the characteristics recorded. The derived parameters are transmitted through the inspect system directly to the burner and process-control systems of the incinerators (Figure 9). Examples for input variables of the control systems are herein the size of the fire source and its intensity. Simultaneously, all of these parameters are visualized via prefabricated interfaces. The inspect system thereby archives all process data in a database and visualize them via Ethernet-coupled graphical user interfaces (e.g. in the control room).

Due to the modular design, the system successfully calculates the combustion characteristics even when there is a wide variety of fuel fractions such as in the cement industry. The system contains e.g. software modules for the connection to multiple camera systems, the analysis of images, a fuzzy control environment, interfaces to process control systems and modules to store images and values in database.

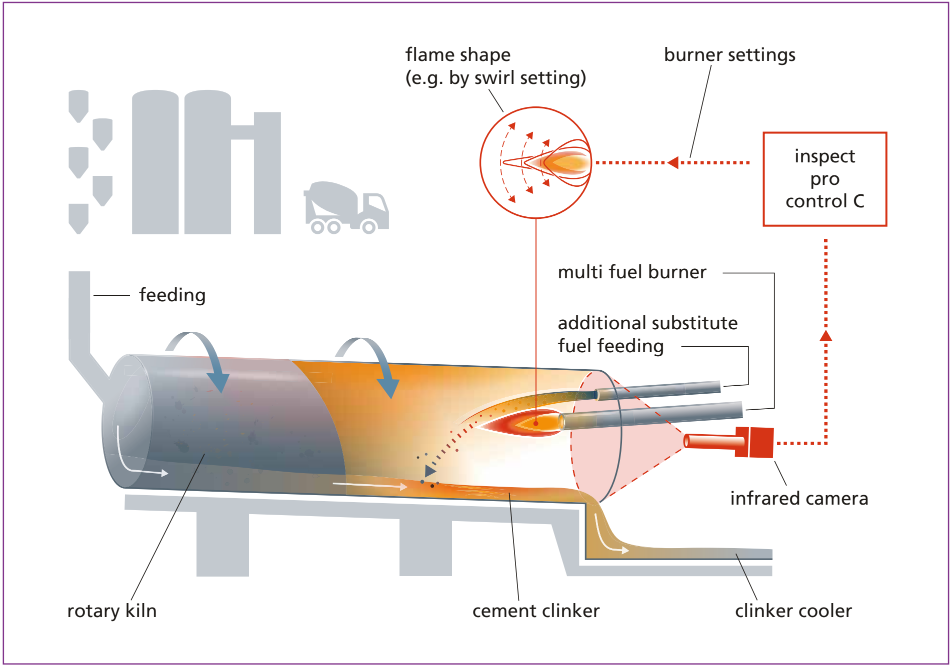

Figure 9: inspect pro control C – control system of a rotary kiln, schematic illustration

Source: ci-Tec GmbH: inspect pro control C. 2016

In summary, characteristic parameters of the burning process are required to achieve, via intervention of the control system, a stable combustion and defined temperature distributions. Hence, a consistently high product quality is reached which is essential for the substitution of oil and coal dust through alternative fuels. Regarding the political framework of sustainability, reducing CO_2, and energy consumption, maintaining a high product quality and increasing the service life of the equipment becomes more and more determined. The development of a control system as presented in this article can significantly contribute to reach these goals. These aspects drive the objective of the Comfeb project and symbolize one motivation to build, develop and refine a secure and reliable process-control software which addresses the referred challenges. Due to the close cooperation in the Comfeb project between ci-tec, the Karlsruhe Institute of Technology, and the cement industry, the development of the inspect system for the cement industry is ensured. The validation of the system as an industrial-ready solution is currently executed at different plants in Germany.

7. Preliminary results of the Comfeb project – an industrial application project – and conclusion

Combustion behaviors of standard fuels with low-rank fuels or pure low-rank fuel combinations are complex and difficult to control. Camera-based measurement and analysis provide non-standard parameters. With their use, the combustion behavior is characterized. Further, the objective of the parameter derivation based on IR-Data is to develop a control system that optimizes the thermal burning process of different fuel fractions.

Currently, the issue of increased alternative fuels and accompanying different burning behavior has not yet been solved, at least to a satisfying state. Moreover, a large part of fuel still consists of fossil fuel to ensure an adequate product quality. Prospectively, the cement producer's ambition is to use more and more alternative fuels to the point where they replace fossil fuels completely. One main problem is that the characteristics of alternative fuels are varying significantly. Thus, the combustion process is partly imperfect which leads to a lower quality of the product. Heat, dust, and permanent rotation further hinder to install measurement equipment inside a rotary kiln.

Remedying this limitation, an infrared camera, which can track fuel particles, will improve the burner operation in several ways. The retrieved data represents the basis of any optimization process with appropriate methods.

In addition to pre-selecting images by analyzing the view conditions, the system also ensures that changes of the camera or burner position do not negatively affect the following image analysis. Hence, the correctness of pre-defined image regions can be guaranteed, which are employed for evaluating and the comparing of the parameters. Moreover, possible false detections caused by cakings are avoided by an appropriate detection method. The estimation and calculation of the fuel streak line not only considers the compact part but also the particles of the fuel. The derived parameters of the system can ultimately be used to support the plant operator or to enable an online and automatic burner control.

Finally, inspect pro control C can be used to retrofit all rotary kiln plants. It allows for reducing energy consumption while still maintaining a high product quality and increasing the service life of the equipment. By adjusting the calculated characteristics using classical methods or fuzzy controls, thermal combustion processes and burning behavior are optimized. Consequently, this optimization results in an increased energy output, decreased emissions of e.g. CO_2, and a stable combustion process. In addition to these benefits, lower operating costs and a reduced use of fossil fuels are further advantages for plant operators.

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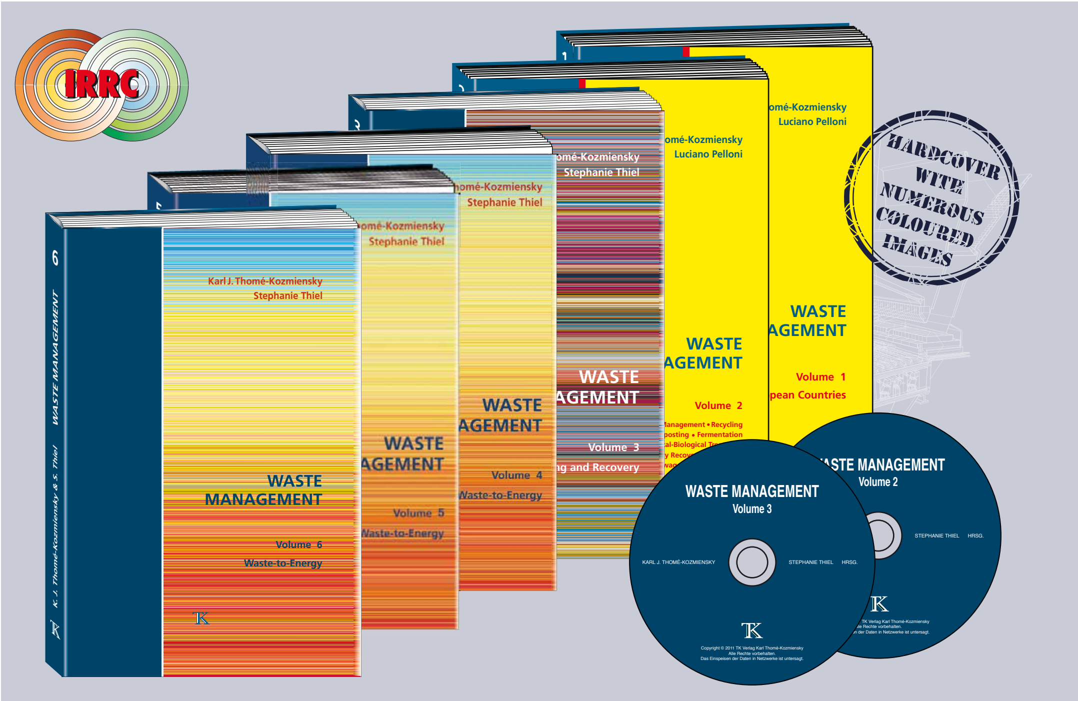

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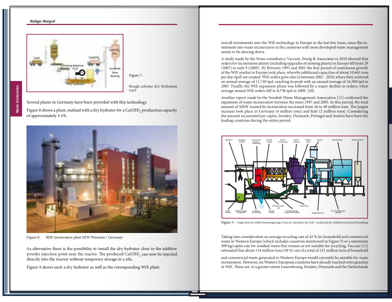

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