

New Methods for the Characterisation of Refuse Derived Fuels and Waste

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1. Introduction

The continuously decreasing availability of fossil fuel resources leads inevitably to increasing prices and bottlenecks in the conventional energy supply.

In that light, the aspect of energy recovery from waste and refused derived fuels (RDF) becomes more important all over Europe. The use of these fuels conserves fossil resources and is an important step towards sustainable energy economy. Especially for the Member States which joined the European Union in 2004 and 2007 this requires considerable investment in waste management.

The primary goals must be to avoid any landfill of untreated municipal waste and to establish incineration and utilization capacities complying with European standards.

RDF is produced from untreated waste and may substitute fossil fuel in several thermal processes. For example in Germany 47 % of the waste input (6,4 m tons p.a.) is combusted in form of RDF [1]. In 2009 the incineration rate (thermal utilization) of municipal waste amounted 33.6 % in Germany. In the Eastern European accession countries this value is between 0.1 and 12 % [2]. Therefore waste-to-energy concepts become a central element in the European waste management. Compared to fossil fuels the compositions of wastes

and RDF are subject to larger fluctuations. Depending on the area of application additional and improved procedures for the characterisation of alternative fuels are needed. Examples include the behaviour of volatile release and the actual heat transfer rates during combustion, especially the flight characteristics of RDF particles in coal fired co-incineration.

2. Fields of application

Two different ways of utilisation evolved in the combustion of waste.

On the one hand untreated waste is disposed directly in mono-incineration plants, exploiting only part of the energy contained. On the other hand waste may be pretreated such that high calorific components can be separated and combusted separately with higher efficiency or better energy recovery. These are the so-called Refuse Derived Fuels (RDF).

RDF incineration is performed in mono-incineration plants as well as in co-incineration situations, where regular fuels can be substituted. Dominant areas of application, as sketched in fig.1, are the cement industry and coal-fired power plants. In mono-incineration plants, for both the waste as well as the RDF combustion, the grate firing predominates. The technical design of these RDF incineration plants, particularly the combustion technology used and flue gas treatment, correspond to waste incinerations plants design [3].

Compared to fossil fuels waste and RDF are subject to a broader range of fluctuations of the combustion properties. These fluctuations and their impact on plant performance are the reason for quality assurance measures which attempt to narrow down the variations.

This may be only partially covered by standard laboratory procedures for an *averaged* sample (with initial masses in the range from 20 to 100 mg) like ultimate and proximate

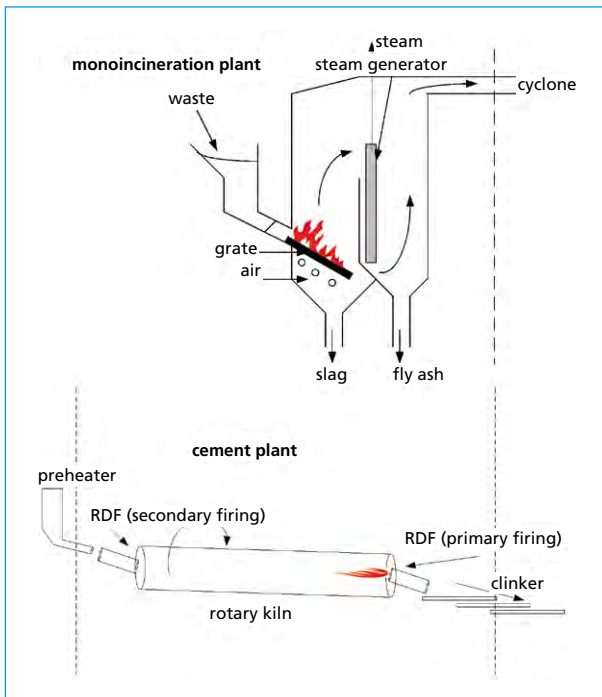


Figure 1:

Thermal use of waste and RDF

analysis supplemented by the determination of the calorific value. This information alone is insufficient to predict the combustion behaviour in the furnace since the particle movement, volatile release and heat transfer characteristics strongly differ from the behaviour of conventional standard fuel particles, thus new approaches are necessary.

2.1. Mono-incineration

Particularly straightforward is the combustion of solid waste on grates where no specific treatment of the incoming waste is required. The waste delivered is first stored in a bunker of the incineration plant and homogenized to a certain degree. Rail crane and grab discontinuously transfer the waste from the bunker into a charging hopper. A loading device pushes the waste on the grate which moves waste through the combustion chamber. Primary air passes the grate and waste layer in a crossflow manner, initiating and sustaining the conversion. In addition to system-dependent conditions, the physical and thermochemical properties of the combustible material have a major influence on the combustion behaviour and the residence time required on the grate.

For a matched design and reliable operation of these plants an appropriate and fairly complete description of the waste and the material fractions it consists of must be obtained.

2.2. RDF in cement plants

The high calorific content of waste, the so-called Refuse Derived Fuel, may be used in addition to fossil fuel in the clinker burning process. The share of RDF of the total fuel energy used by the German cement industry was 61 % in 2010 [4]. RDF is a suitable fuel for application in two components of cement plants, namely the calciner and the primary flame in the rotary kiln (Figure 1). While the latter is very sensitive to fluctuations and changes of fuel parameters like volatiles or particle size, the conditions in the calciner are much more *forgiving* and the sensitivity on fuel properties is less pronounced.

The use of RDF in cement plants requires a treatment of suitable waste with appropriate quality. In spite of treatment the use of RDF in the main burner leads to a change in the flame characteristic (ignitability, flame stability and flame shape).

Due to a different content of volatile components there is a change in the local heat transfer conditions. This is especially the case when large amounts of RDF are used. In the gas phase in clinker processes combustion temperatures about 1,600 °C must be achieved. Reductive conditions in the material bed should be avoided. Therefore, contrary to the oven charge and calciner firing, in the primary firing only high calorific and lightweight RDF are used.

3. Fuel characterisation

As already mentioned in the last sections a comprehensive characterisation of fuel is of great importance. The basis for this is always the sampling, which is adapted to the specific fuel.

3.1. Conventional sampling and preparation

The aim of the sampling procedure is to obtain subsets of the combustible material, which are suitable to determine properties of the fuel which are representative, characteristic and relevant for the combustion process. The representativeness of these subsets concerning the parameters which are to detect, is very important.

Basic requirement for this sampling is a sampling plan. Based on this all samples are taken and analysed. The sampling plan guarantees that the statistical spread of the results is not influenced by changing sampling methods. In the following a suitable method for sampling of municipal solid wastes will be presented which was developed by Fraunhofer UMSICHT. It is based on the sampling directive LAGA PN 98 [5]. The method is designed for sampling of waste delivery vehicles, but it can be adapted easily to deviant circumstances.

Sampling of RDF is easier when it takes place directly on the preparer's conveyor belt. Here are no special measures necessary and relevant sampling specifications (see [5, 6]) can be applied.

3.1.1. Reduction of sample subsets

The transport-volume of waste delivery vehicles has a range from 50 to 100 m³. A reasonable sample size should be around 700 dm³. According to the procedural method of ground analysis (DIN ISO 10381-1 (2003)) a defined pattern of sample points of the heap of waste dumped from the vehicle is necessary. The sample points should be spread equally spaced across the pile of waste. This can be achieved through a chess pattern, where *knight steps* define the next sample point. The samples removed are mixed and lead to an average sample.

3.1.2. Sample conditioning

The next step after sampling is the conditioning of the samples. At first all large inert extraneous materials are separated, weighted and rejected. Then the whole 700 dm³ sample is shred with a single-shaft-shredder to a particle size smaller than 20 mm. Now samples are taken from the output of the shredder. The amount of samples depends on the particle size and material heterogeneity. These samples are united again to four average samples. Two of the average samples are reduced to a laboratory amount, embrittled with liquid nitrogen and milled to a size smaller than 1 mm. These samples can be analysed in the laboratory. The other two samples are used to detect moisture content. In the following the determination of the moisture content and the calorific value are described.

3.1.3. Conventional average parameter analysis

The sample moisture is very important information (great impact on heating value) and should not be influenced through the sample preparation. Therefore after each preparation step the moisture content should be analysed. The detection of moisture through drying is done at 65 °C for at least 15 h until mass consistency is achieved (deviating from the regular methods like DIN 38 409, which proposes 105 °C). This prevents the unwanted release of volatile matter.

The higher heating value $H_{s,d}$ (d=dry) describes the amount of heat which is released during complete combustion of one kg of the sample including the sensible and latent heat of the water which is included or formed through chemical reactions. The detection of $H_{s,d}$ can be carried out with a bomb calorimeter. The determination of the lower calorific value H_i is computed with higher calorific value $H_{s,d}$, hydrogen content H and moisture content FH [13].

$$H_i = (H_{s,d} - 212,2 \cdot H) \cdot (1 - 0,01 \cdot FH) - 24,43 \cdot FH \text{ in } \frac{\text{kJ}}{\text{kg}} \quad (1)$$

If the elementary analysis is lacking, a reduction of 8 percent of the higher calorific value leads to the inferior calorific value (based on the dry substance) [6].

If the average calorific value of the waste which is burnt during one year is to be analysed, the weather conditions and other seasonal influences have to be reconsidered.

3.2. Time- and temperature-resolved fuel analysis

The particle ignition and burn-out highly depends on its volatile release behaviour. The fire position on the grate or the flame length in a blast furnace process is influenced by this, but conventional sum parameter analysis does not give results for a better understanding regarding RDF. That is why, in addition to the conventional thermochemical laboratory analysis, some advanced, non-standardized analysis methods were necessary and are now available which allow the determination of details on the release of volatiles.

3.2.1. Volatile release by Fingerprint

The volatile fraction contained in fuels is a significant parameter strongly influencing the combustion behaviour. RDF with a large amount of plastic material shows a higher rate of volatile release which may lead to faster ignition and combustion and tends to lead to higher local temperatures in the combustion chamber.

Based on this, a first classification of the fuel by the laboratory proximate analysis is possible. This analysis comprises the determination of the content of humidity, ash, volatile matter and the fixed carbon fraction.

However, this knowledge alone does not reveal information about the temperature-dependence of the mass release behaviour of the volatiles. For this reason a conventional elementary analysis in the CHN analyser was converted into the Fraunhofer *Fingerprint* method. *Fingerprint* terms a release profile, which detects the distribution of the calorific inventory of volatile matter and the residual coke released at different temperatures.

Using a modified CHN-analyser it is now possible to restrict the measurement of the elemental composition to the volatiles. When the volatiles are released at different temperatures, the calorific-release profile can be depicted as a function of the release temperature with the aid of model equations (according to BOIE [7] or Channiwala [8]). In Figure 2 the measurement principle is graphically represented.

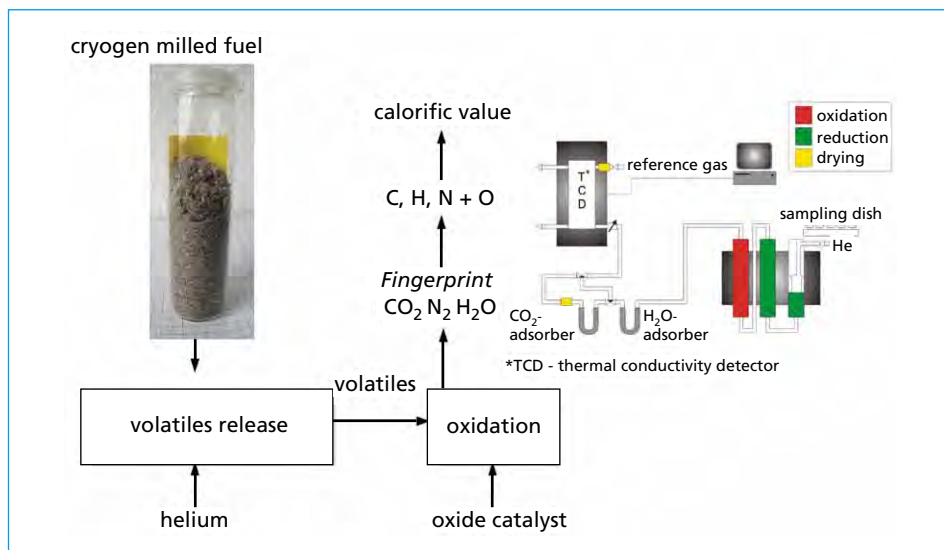


Figure 2: *Fingerprint* method

Source: Marzi, T.; Keldenich, K.; Görner, K.: Energetische Verwertung von Ersatzbrennstoffen – Entwicklung einer Methodik zur Erfassung der feuerungstechnischen Brennstoffeigenschaften. Müll und Abfall, Mai 2005, S. 572-579

The *Fingerprint* method was used to analyse the devolatilisation of a RDF-sample and a municipal solid waste (MSW) sample in the temperature range between 300 °C and 900 °C. Results of this analysis are given in Figure 3. It shows that, at the same temperature released RDF volatiles contain significant more energy than volatiles of MSW. This was expected due to the higher calorific value and plastic content of the RDF.

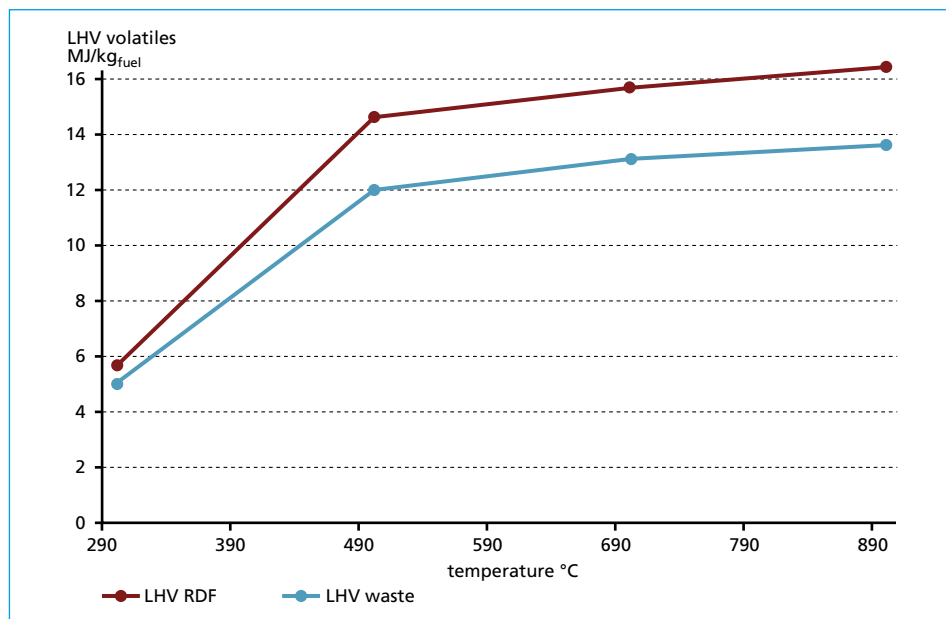


Figure 3: Volatile release profile (calorific value) RDF and MSW

The obtained data can be used to make statements about the ignitability of the fuels at certain temperatures. The data can also be implemented in combustion models and therefore used for plant and optimisation design.

3.2.2. Thermochemical and physical characterisation by LOKI

As already mentioned the determination of the overall volatile content is state of the art and can be ordered from any ordinary fuel laboratory. Here usually weights between 10 and 100 mg of fine milled fuels are used, which assumes homogeneous material properties. However the thermo-gravimetric and thermo-chemical investigation of heterogeneous fuels to determine their conversion requires larger samples for analysis.

Thus, new technological solutions which account for the heterogeneity of the fuel are needed [10]. For this reason, several pilot plants have been already developed (e.g. KLEAA [11]). Previous investigations on the combustion behaviour with larger amounts of fuel are mostly restricted to a single-stage thermal decomposition in an oxidizing atmosphere. A partitioned investigation of the overall combustion considering the individual overlapping sub-steps like degasification and subsequent char burnout was not completed yet.

However, an isolated view of the individual steps is an advantage, when individual conversion steps have to be recorded or related models must be checked. Therefore at Fraunhofer UMSICHT an apparatus has been developed which transfers the known pyrolytic

thermo-gravimetry from the laboratory to a pilot plant scale. This allows analysis of larger fuel samples in the range of 50 to 500 g and with approximate original fuel geometry (up to 150 mm). By a downstream oxidation zone and conventional CO_2 - H_2O -gas analysis, the *Fingerprint* method can also be transferred to a plant scale. In addition, drying and degasification can be separately determined from thermo-gravimetric studies and the H/C ratio can be detected as a function of time and temperature. To obtain information about the macro-kinetics (superposition of chemical kinetics, mass and heat transport at different particle sizes, etc.), the test facility is equipped with various temperature measuring devices. These thermocouples can be placed in the oven zone and in the core of a fuel particle. The presented experimental apparatus provide a range of investigative possibilities for conversion behaviour, heat transport, ignition temperature, drying rate, etc.

This Large-scale Oven for Kinetics Investigation (LOKI), which extends the laboratory method, consists of two oven zones made of quartz glass (see Figure 4). The lower zone (OZ1) can be operated with preheated air or nitrogen, the upper zone (OZ2) is operated with air and serves as post combustion zone. Separation of the two zones is provided by a frit. This frit has two functions: it thermally insulates the two zones, and on the other hand it homogenizes the flow by a controlled pressure drop. The two zones can be heated separately. In OZ1 a batch of up to 500 g of bulky solid fuel (e.g. RDF) can be placed in a basket which is linked to a scale. The oven surrounding is built of a fused quartz glass pipe. Its length is approx. 1.9 m and its diameter is approx. 0.2 m. Placed around the pipe are two radiant heaters which can be controlled separately. Maximum heating temperature is up to 1,000 °C, maximum heating rate of the apparatus is approx. 40 K/min. The carrying gas, which flows through both oven zones, is fed in below the lower oven zone. This flow

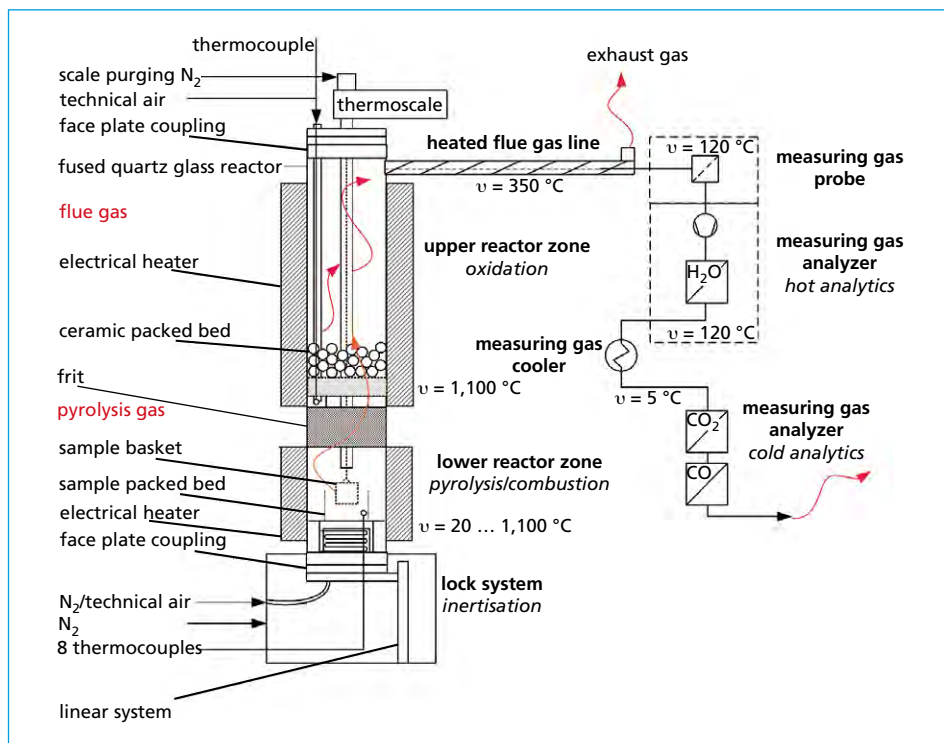


Figure 4: Sketch of LOKI

may consist of nitrogen or a mixture of nitrogen and technical air. In this article pyrolysis procedure and its results will be shown. Gas flow between 1...50 l/min is possible. The upper oven zone, which suites as post-combustion zone, is supplied with technical air with 1...25 l/min. With the help of thermocouples, the heat transport through the oven radiation in to the fuel bed, placed in the lower oven zone, can be detected.

Below the lower oven zone a lock system is positioned. The lock allows a quick insertion of the fuel sample in an already heated oven zone and a sudden heating of the sample. The downstream flue gas analysis (NDIR-Spectroscopy) takes 1 l/min out of the flue gas stream and measures continuously the molecular composition of the flue gases (CO₂ and H₂O). This allows to calculate the elemental composition of the reacted fuel with regard to H, C and O (neglecting of N).

Figure 5 shows the release of CO₂ and H₂O as a function of temperature and time for a waste sample (59 g, 18 w% moisture). During pyrolysis tests the sample is placed in the scale basket. The lower oven zone is supplied with nitrogen (0.167 l/s) and the upper oven zone with technical air (0.083 l/s).

During the test mass loss, inner oven temperature and flue gas concentrations are measured. Relevant measurement values for the analysis are fed nitrogen (N_{2,OZ1}, N_{2,scale} in l/s), fed air (air_{OZ2} in l/s), gas concentrations of CO₂ (in Vol.-%), H₂O (in Vol.-%) and inner (T_OZ1 in °C) and outer (T_heater_OZ1 in °C) oven temperature of the lower oven zone.

Simultaneous the mass loss (scale in g) as a function of time is represented. The fuel consists mainly of plastics, textiles, paper, wood and fine waste. After drying of the sample there are two release phases noticeable from mass loss and gas concentrations. The first occurs in the temperature range between 200 °C and 300 °C. The second release phase occurs at temperatures above 320 °C. 63 w% of the fuel are decomposed and released as volatiles with a heating rate of 5 K/min and a final temperature of 600 °C.

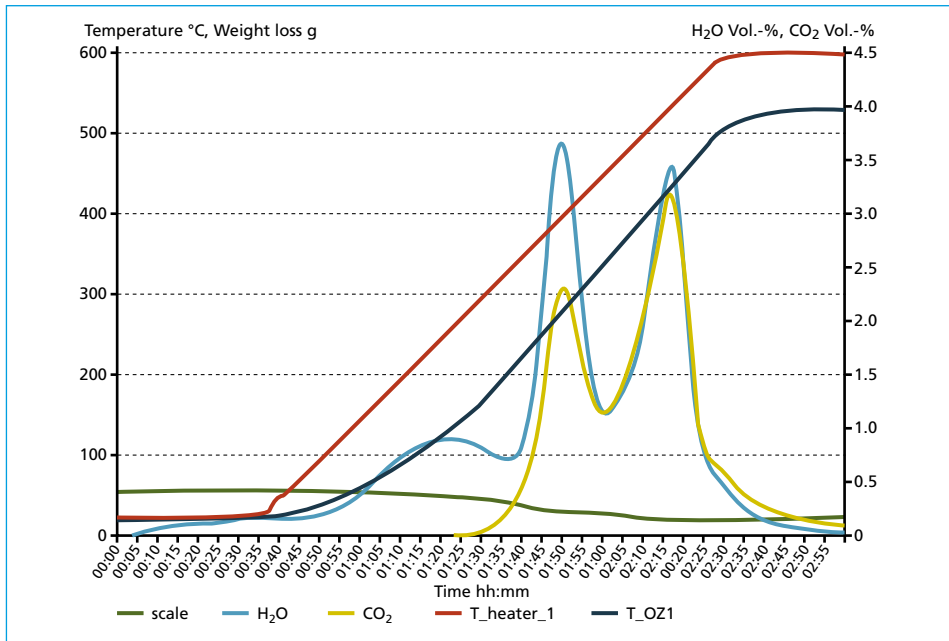


Figure 5: Waste pyrolysis test, measuring of mass loss, CO₂ and H₂O flue gas concentration

3.3. Aerodynamic characterisations of RDF particles by KEPF

Refuse Derived Fuel (RDF) originates from crushed and conditioned waste. As a result, RDF consists of large particles and has a very heterogeneous composition regarding material, particle geometry, and thermo-chemical properties. That is why its use as a substitute in blast furnace processes (e.g. rotary kiln) leads to difficulties in handling.

The aerodynamic properties of RDF particles depend on the physical properties (size, geometry, mass) and strongly differ from coal dust and vary because of the heterogeneous composition. This makes it hard to predict and control the burning process and changes in the flame geometry and temperature profile are resulting. That is why further investigations on the flight characteristics of RDF were necessary and have been undertaken.

So far no simulative description of RDF existed, due to the lack of sufficiently detailed RDF data and appropriate numerical models. With the current state of numerical simulation-technologies it was possible to simulate small (< 1 mm) spherical particles (e.g. coal dust) in turbulent flow fields with sufficient accuracy. But these simulation technologies are not suitable for RDF, because the movement of particles with a larger size also depend on the physical properties of the particles. Furthermore the inhomogeneity of the particle geometry leads to fluctuations in particle velocities.

In order to improve this situation a camera equipped vertical drop shaft was developed at Fraunhofer UMSICHT in cooperation with the Department of Energy Plant Technology of the Ruhr University of Bochum. It was used to measure the individual trajectories of a large number of RDF particles as a function of their physical properties (size, geometry, mass) in a stagnant flow. For several material fractions of the RDF, frequency distributions of settling velocities, drag coefficients and radial dispersion were derived from the measurements.

The movement of particles, particularly the relative velocity of the particle depends on size, geometry and mass. Because of this the analysis consists of two steps. The first step includes an analysis of the physical properties, where a combination of scale and photography is used (the so called photoscale). The RDF-particle is weighed and two pictures of the particle are taken by different cameras. The particle contours are detected automatically in each picture as a result of the brightness. The detection of a particle is shown in Figure 8, Figure 6 schematically shows the scale. With this information received from the two cameras (vertical and horizontal profile) the geometric characteristics such as dimensions, volume and shape factor were calculated.

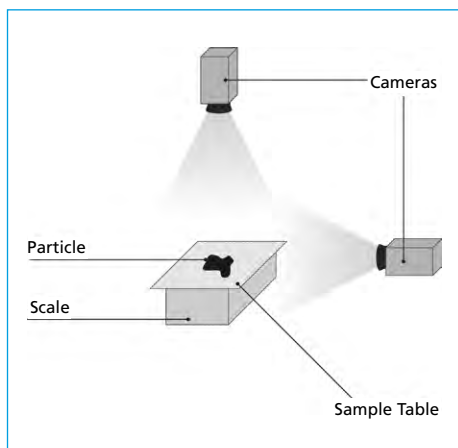
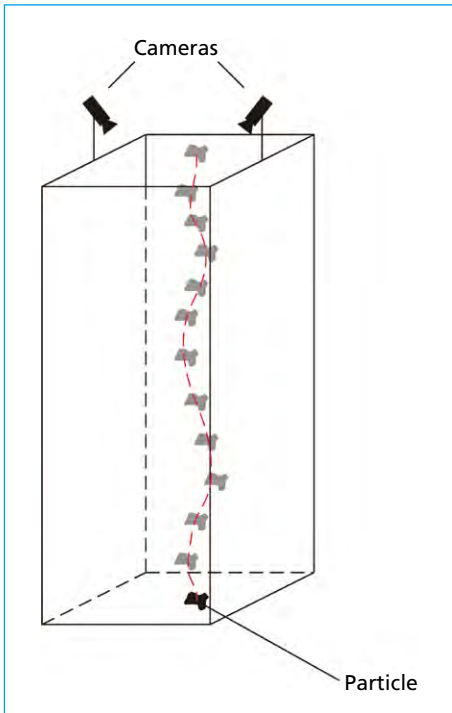


Figure 6: Schematic design of the photoscale

In the second step, the trajectories of falling RDF-particles were recorded in the drop shaft, using two cameras, which were mounted orthogonal to each other at the top of the drop shaft. The actual position of the particle can be calculated from the picture pairs taken by the cameras and the information on particle geometry obtained earlier from the fotoscale. This lead to a time resolved velocity calculation of the movement vector for each particle. Figure 7 schematically shows the drop shaft.

The geometric data and the data describing the aerodynamic behavior of RDF-particles were used as input and boundary conditions for the simulation of the movement of RDF-particles.



In line with the aim of transferring the results to power plants or rotary kilns, experimental investigations of the injection of RDF in an air classifier were done. The injected RDF-particles were separated according to the aerodynamic properties and then analyzed with the methods described above. These results were compared with simulations of the air classifier. In Figure 9 the simulation results (trajectories) of two RDF-fractions are shown. The particles of the bright trajectories are more spherical than the particles of the dark trajectories. For all classes of RDF-particles, consistent results compared to the experiment were obtained.

Figure 7: Schematic design of the drop shaft

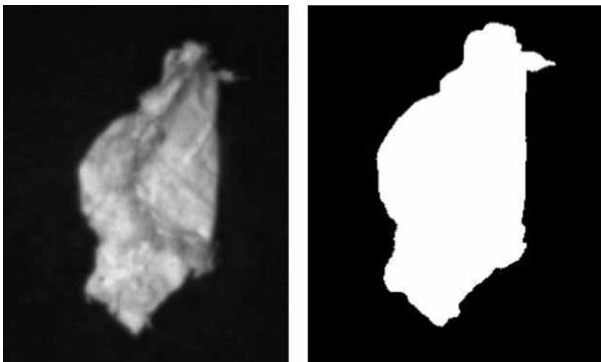


Figure 8:

Detection of a RDF-particle



Figure 9:

Simulation of the RDF-Separation in an air classifier

Source: Krüger, B.; Wirtz, S.; Marzi, T.: Modellierung der pneumatischen Förderereigenschaften von Ersatzbrennstoff. UMSICHT zur Sache, Oberhausen 2010.

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