Solid recovered fuels — Determination of combustion behaviour

ICS 75.160.10

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British Standards

National foreword

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Verbrennungsverhaltens

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Foreword

This document (CEN/TR 15716:2008) has been prepared by Technical Committee CEN/TC 343 "Solid recovered fuels", the secretariat of which is held by SFS.

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Introduction

Historically, SRF goes back to the oil crises approximately 30 years ago, when refused derived fuel (RDF) was promoted as a substitute low cost fuel. Contrary to that situation, the producers of SRF took the initiative for the implementation of a quality system to meet and guarantee specified fuel classification and specification parameters. Quality systems to check their production now exist in several EU member states and efforts are being made by CEN/TC 343 to develop European Standards for SRF [1].

The production and thermal utilisation (energy recovery) of Solid Recovered Fuels (SRF) from bio wastes, residues, mixed- and mono waste streams have significant relevance as a key component of an integrated waste management concept.

The implementation of SRF production in an integrated waste management concept demands a potential market for these products. Known proven markets are found in the European energy sector and in other more product-oriented sectors like cement or lime industry by substitution of fossil fuels. The capacities for co-utilisation of these products, to include utilisation in minor thermal shares, are enormous, especially in the new European member states as most of the energy production of these countries relies on fossil fuels.

A successful application of solid recovered fuel in power plants and industrial furnaces would require a thorough understanding of the fuel properties which include the combustion behaviour, emission potential, impact on facility etc. The determination of combustion behaviour which is the main focus of this document seeks to outline possible methods and procedures that can be adopted to analyse any given solid recovered fuel. An approach has therefore been outlined where the determination of combustion behaviour is categorised into four groups which combine to give a holistic impression of the combustion progress of SRF in both mono and co-firing systems (see Figure 1).
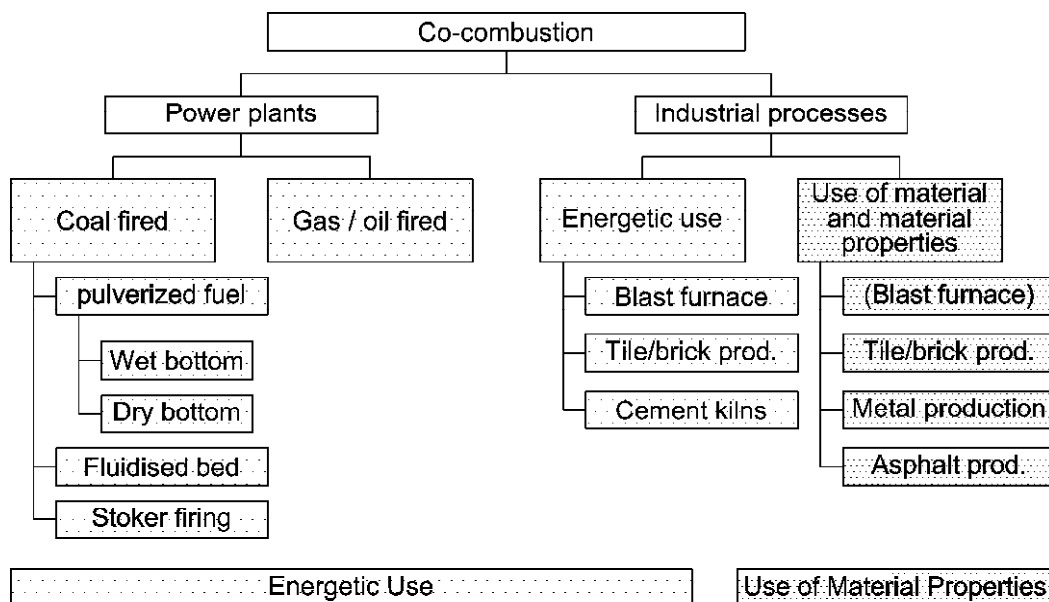
Figure 1 — Scheme to determine combustion behaviour of SRF

While there are standardised methods, such as from the American Society for Testing and Materials (ASTM) and the German Institute for Standardization (DIN Deutsches Institut für Normung e. V.), for determining combustion behaviour for primary fuels (e.g. coal), the process is not the same for SRF. At present, there are no standardised methods for SRF. Most of the available methods are in-house, usually designed for particular types of SRF, e.g. waste, or bio-residue fractions to suit a specific combustion system like grate firing, fluidised bed, pulverised fuel system, and cement kiln. Figure 2 gives an overview about the broad variety of

SRF utilisation routes using an example of co-combustion in power plants and industrial furnaces. Co-combustion also includes indirect co-firing systems such as gasification (Lahti, Zeltweg) and pyrolysis (ConTherm). While the environmental aspect of the thermal utilisation of SRF is very important, this report focuses only on the combustion aspect.
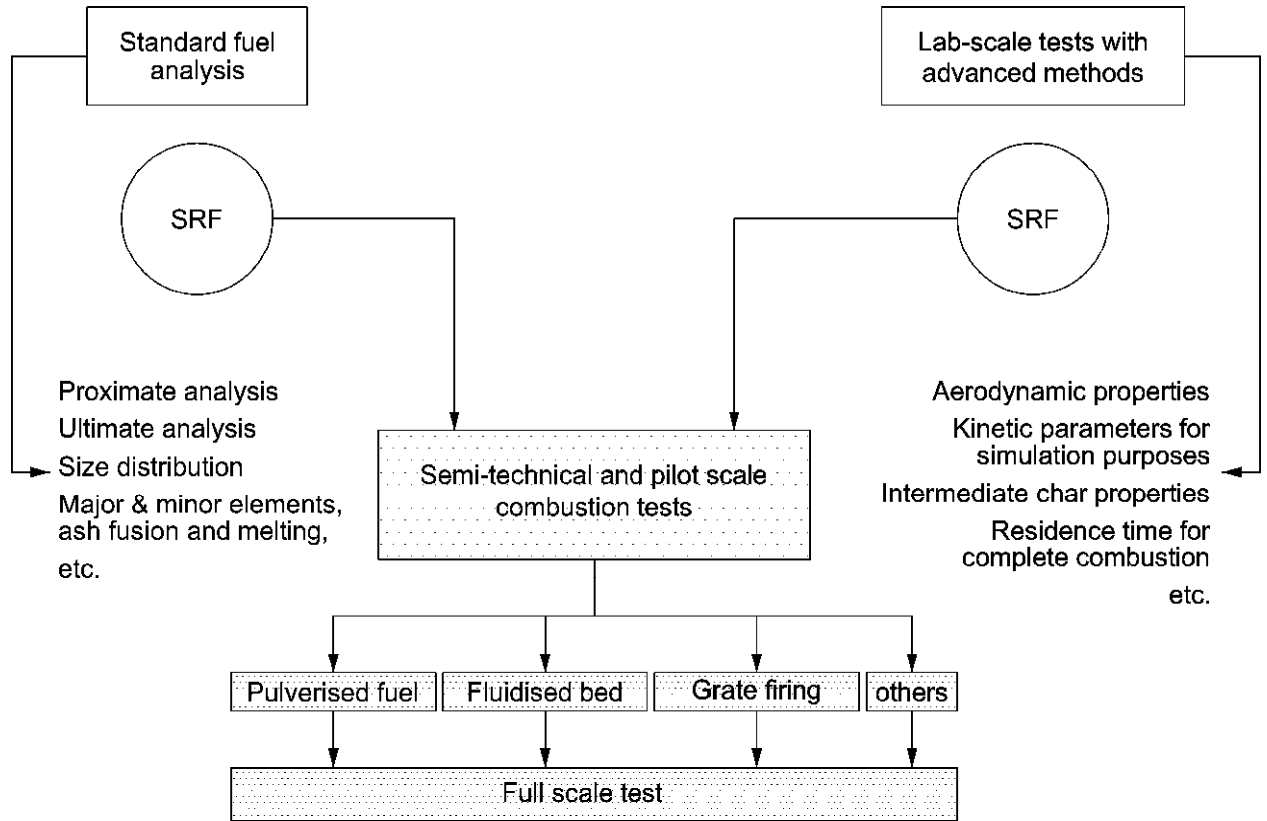
Figure 2 — SRF utilisation routes

Solid recovered fuel can be made of any combustible non-hazardous waste and processed to a quality that allows to classify it in accordance with CEN/TS 15359 and which fulfils specifications as agreed with the customer. Considering this, the main problem becomes obvious: How to define reliable methods to describe the combustion behaviour of solid fuels such as SRF, valid for all possible types of input material and combustion systems? A systematic approach adopted herein to determine combustion behaviour is outlined in Figure 1. It is grouped into four categories:

— standard fuel analysis;

— laboratory-scale tests with advanced methods;

— semi-technical and pilot-scale combustion tests;

— full-scale test.

In general, such a four-step procedure is an effective way to successfully integrate a new fuel in an existing power plant or an industrial furnace. In any case, full scale tests are the most reliable but very expensive with several bottlenecks (e.g. retrofits, permits, time, etc.) and that is the reason for the need to develop and standardise methods which are reliable, fast, and not expensive according to the various firing systems are essential. Besides the evaluation of parameters concerning combustion behaviour, the steps before full scale implementation also forms substantial basis to reliably evaluate other areas of major interest such as grinding and fuel feeding; slagging, fouling and corrosion; and lastly emissions and residues. The systematic evaluation of these additional topics requires area specific analyses, tests, and measurements.

Concerning combustion behaviour, the standard analysis of the SRF will determine the basic parameters about the combustible and incombustible matter. The amount of energy, the contents of water, volatiles, fixed-carbon, ash, and particle size will roughly dictate the type of the combustion system that is best suited. In addition to the standard analysis, a selected combustion system might require an advanced parameter analysis, if possible, with a close relation to case specific process parameters. Such a correlation will substantially enhance the reliability of transfer studies. An example, in the case of a pulverised firing system, is the maximum particle size required for a complete combustion in order to avoid fuel plummeting into the bottom ash.

Currently, the activities towards the combustion behaviour of SRF rely largely on standard analysis and laboratory-scale tests, which were originally developed with certain limitations and applicable to solid fuels such as lignite and hard coal. A common problem of these methods is that parameters related to SRF during combustion are not sufficiently covered. These methods make sure consistent quality of the SRF supply rather than to predict combustion performance. Therefore, the development of the so-called advanced test methods to fill the gap and amending existing test apparatus and measurement conditions is required.

The driving force to introduce SRF rests much on economic factors. In most cases, the end user will be either the operator of a power plant or an industrial furnace. The primary focus will be an unrestricted and reliable operation of the facility. One wants to assess the possible risks and dangers. In case of retrofits, the end user needs to calculate the required cost on modifications and operation. It can be assumed that due to possible operational risks such as corrosion, the plant operators will select the fuel with the most appropriate qualities. Such requirements are needed tools to control the quality of the SRF and to deliver them according to specification. As such, the knowledge of the combustion behaviour is an essential aspect for the commercialisation of SRF. It will allow the optimisation of the process and the assessment of possible risks and dangers prior to full-scale application.

Some methods and parameters will be introduced in the subsequent sections, but whatever methods are to be used in the future should be orientated towards the following aspects:

— reproducibility;

— repeatability;

— reliability;

— time efforts (rapid test methods);

— cost effectiveness;

— possibilities for automatic testing.

The authors summarise and refer to past and current activities trying to describe combustion behaviour of SRF. The idea is to identify a common and successful practice where various approaches converge.

1 Scope

This Technical Report gives a review on determination methods for exploring how different SRFs behave in different combustion systems, e.g. with respect to time for ignition, time for gas phase burning and time for char burn out, including information on technical aspects like slagging and fouling, corrosion as well as required flue gas cleaning for meeting the emission limit values induced by the Waste Incineration Directive (WID).

2 Combustion of solid fuels

2.1 Basis of solid fuel combustion

Combustion of fuels shall be considered both from theoretical and practical perspectives. The former can define combustion as the rapid chemical reaction of oxygen with the combustible elements of a fuel. While the later where the engineer is concerned with boiler design and performance might define combustion as the chemical union of fuel combustibles and the oxygen of the air, controlled at a rate that produces useful heat energy. The two definitions implicitly consider many key factors. For complete combustion within a furnace, four basic criteria shall be satisfied:

1) adequate quantity of air (oxygen) supplied to the fuel;

2) oxygen and fuel thoroughly mixed (turbulence);

3) fuel-air mixture maintained at or above the ignition temperature;

4) furnace volume large enough to give the mixture time for complete combustion.

Quantities of combustible constituents within the fuel vary by types. Figure 3 shows the significant change in the combustion air requirements for various fuels, resulting from changes in fuel composition. It illustrates the minimum combustion air theoretically required to support complete combustion.

Key
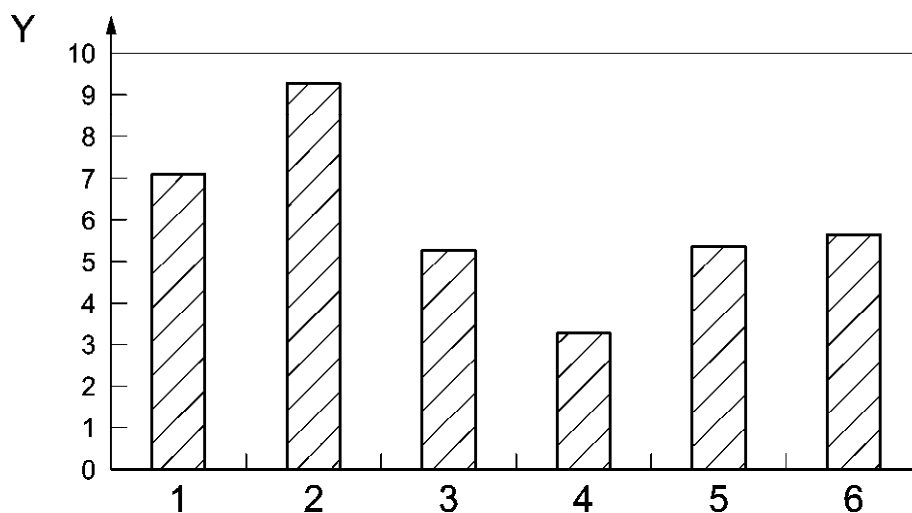
Y   Stochiometric air demand in nominal cubic meter dry air per kilogram fuel

Figure 3 —Stoichiometric air to fuel ratio for some SRFs

In an ideal situation, the combustion process would occur with the stoichiometric quantities of oxygen and a combustible based on underlying chemical principles. However, since complete mixing of air and fuel within the furnace is virtually impossible, excess air shall be supplied to the combustion process to ensure complete combustion. The amount of excess air that should be provided varies with the fuel, boiler load, and type of firing system, and it is in the range of $0,1 \leq \lambda \leq 0,6$ or even more.

Solid fuel combustion consists of three relatively distinct but overlapping phases:

— heating phase (time to ignition);

— gas phase combustion (time of gas phase burning);

— char combustion (time for char burnout).

Firstly, the time to ignition involves particle heat up due to radiation and convection in the furnace driving off moisture and volatiles adsorbed in the solid. Solid fuels, especially fresh biomass, can release combustible volatiles below 100°C and ignition can occur as soon as the particle is not completely surrounded by water vapour. The time to ignition is relatively short. For plastics it is different, they do not contain volatiles in the traditional meaning. They are often transparent so they heat up slowly and then start melting. Film plastics tend to shrink and form molten droplets. At about 400°C de-polymerization starts (pyrolysis) where gaseous combustible compounds release. The time to ignition is long compared to regular fuels of the same particle size. Secondly, the time of gas phase burning involves the volatiles released through desorption and pyrolysis burn in a flame around the particle until a solid char is left. This phase is long for plastics compared to coal because plastics (except PVC) do not form a char at all. The flaming particle can fly as a warm air balloon. Thirdly, the time for char burnout is a gas/solid reaction which for coal is the longest step and it is strongly dependent on particle size and porosity etc. For wood this is intermediate and for polyolefin plastics it is close to zero. The tests indicate that, for particles of the same size (50 mg) and same temperatures and oxygen contents, the time for complete burning is in the following order: plastics < dry wood < coal.

The combustion process of metals present in SRF especially aluminium is complicated and cannot be completely avoided. Ignition of such particles is preceded by the disruption of the oxide film at a temperature > 1500°C (calculated); it react intensively with atmospheric oxygen, which leads to a further sharp increase in temperature of the particle surface zone (see [2]). These high temperature regimes required to start the ignition are usually not found in conventional boilers, therefore the molten aluminium droplets coagulate and form large pieces upon cooling.

2.2   Basics of some common combustion systems that utilises SRF

Pulverised fuel combustion system (PF): In PF combustion, the fuel is ground to a specified fineness, e.g. coal to a maximum particle size of 250 µm to 300 µm, depending on the reactivity. They are pneumatically transported to the burners and injected via particle-laden jets into the combustion chamber. For lower reactivity fuels, the fineness of grind is increased to create a larger specific surface area so as to improve conditions for ignition and combustion. The transport air that carries the fuel from the mill to the burners is a small fraction of the total combustion air. It is kept at low temperature, limited to about 373 K for coal and for SRF much lower, for reasons of safety against ignition and explosion in the mill and in the pulverized fuel transport pipeline between the mill and the burners. The rest of the combustion air, which can be preheated to higher temperatures, is injected separately and admixed with the already ignited particle-laden jet in the combustion chamber. The combustion chamber is typically of parallelepiped shape; the cross-sectional area of a 300-MW coal-fired boiler would be about 15 m × 15 m and its height 45 m to 50 m (see [3]).

Fluidised Bed system: A fluidised bed is composed of fuel (coal, coke, biomass, SRF, etc.) and bed material (ash, sand and/or sorbent) contained within an atmospheric or pressurised vessel. The bed becomes fluidised when air or other gas flows upwards at a velocity sufficient to expand the bed. At low fluidising velocities (0,9 m/s to 3 m/s), relative high solid densities are maintained in the bed and only a small fraction of the solids are entrained from the bed. A fluidised bed that is operated in this range is referred to as a bubbling fluidising bed (BFB). As the fluidising velocity is increased, smaller particles are entrained in the gas stream and transported out of the bed. The bed surface becomes more diffuse and solids densities are reduced in the

bed. A fluidised bed that is operated at velocities in the range of 3,9 m/s to 6,7 m/s is referred to as circulating fluidised bed (CFB) (see [4]).

Fluidised bed combustion (FBC) units are touted as being „fuel flexible", with the capacity of firing a wide range of solid fuel with varying heating value, ash content, and moisture content. Also, slagging and fouling tendencies are minimised in FBC units because of law combustion temperatures. The advantages of FBC in comparison to conventional pulverised fuelled units can be summarised as follows:

— SO_2 can be removed in the combustion process by adding limestone to the fluidised bed, eliminating the need for an external desulphurisation process;

— fluidised bed boilers are inherently fuel flexible and, and with proper design provisions, can burn a variety of fuels;

— the combustion in FBC units takes place at temperatures below the ash fusion temperatures of most fuels, consequently, tendencies for slagging and fouling are reduced with FBC;

— because of the reduced combustion temperatures, NO_x emissions are inherently low.

Stoker firing system: In this firing system, solid fuel is spread and combusted on a grate system. The grate usually used is a continuous-cleaning, travelling grate. The lighter portion of the solid fuel burns in suspension above the grate and the heavier portion burns on the grate. Air and or water banks are used to cool the grate. Sometimes cooling is done by water. An over-fire combustion air is used to cause mixing of gases and combustion above the grate. This system is used predominantly for processed as well as unprocessed solid waste combustion. Other technologies used to generate heat and power from SRFs are explained in details elsewhere (see [5]).

2.3   Determination of characteristic parameters

Several researchers (see [6], [7], [8]) have shown that particle size and reactive surface have large influence on the combustion process, most especially SRF and solid biomass qualities available on the market. The distinctions between fuel properties and process conditions which contribute to the total combustion process are outlined in Table 1. Fuel properties and process parameters (operational conditions) together define how a particular SRF behave during combustion.

Table 1 — Fuel and process parameters influencing the combustion behaviour of SRF

Fuel properties	Process parameters
Heat capacity and conductivity	Temperature profile in the furnace
Gross calorific (GCV) and net calorific value (NCV)	Heat transfer in the furnace
Composition and distribution of organic and inorganic matter	Oxygen partial pressure along the furnace profile
Volatile release and char reactivity as a function of the particle temperature	Velocities, turbulence and mixing behaviour
Ash composition and ash fusion behaviour	Residence time
Fuel particle size etc.	Combustion system etc.

Solid fuel properties can be distinguished into chemical, mechanical (physical), calorific, and kinetic (reaction) properties. The chemical properties describe aspects like burnable substances, major and minor elements, etc. The mechanical properties describe particle and bulk densities, particle size distribution, shape and form, etc.; whereas the heating value, air demand, heat capacity and the calculated adiabatic flame temperature describe the calorific properties. These parameters can be transferred to SRF without restriction. The evaluation of kinetic properties is more difficult as they depend on chemical, mechanical, and calorific

properties. Contrary to the procedures used for coals, where detailed investigations towards the combustion properties are performed as a function of volatile content, heating value or particle size distribution, the approach even though not totally suitable for heterogeneous fuel can be adopted after a few modifications.

2.4   Use of classification numbers

Some parameters for the combustion behaviour of fuel are indicated by different classification numbers (see [9], [10]). This can be used to compare different primary and secondary fuels. Classification numbers are also published for other areas of interest such as slagging, fouling, corrosion and emission formation. A transfer of these numbers, which are mainly applied to different coal qualities, to SRF will have more limitation. However, it could be an option in the classification of SRF, although the interaction with coal in case of co-incinerator cannot be described sufficiently with this approach. Nevertheless, the approval of such classification numbers should include an independent validation procedure.

2.5   Combustion prediction tool

For the development and successful implementation of particle combustion models into combustion predicting tools, such as computational fluid dynamic (CFD) calculations, the kinetics of the fuel slagging; specifically volatile and char kinetic data are of great interest. The former is paramount if de-volatilisation is the rate determining step of the SRF during combustion, and vice versa. Most SRF have high volatile content, and during combustion their release dictates the process. Figures 4 and 5 illustrate the interactions in the combustion model as captured in CFD modules for plastics biomass and coal [11].
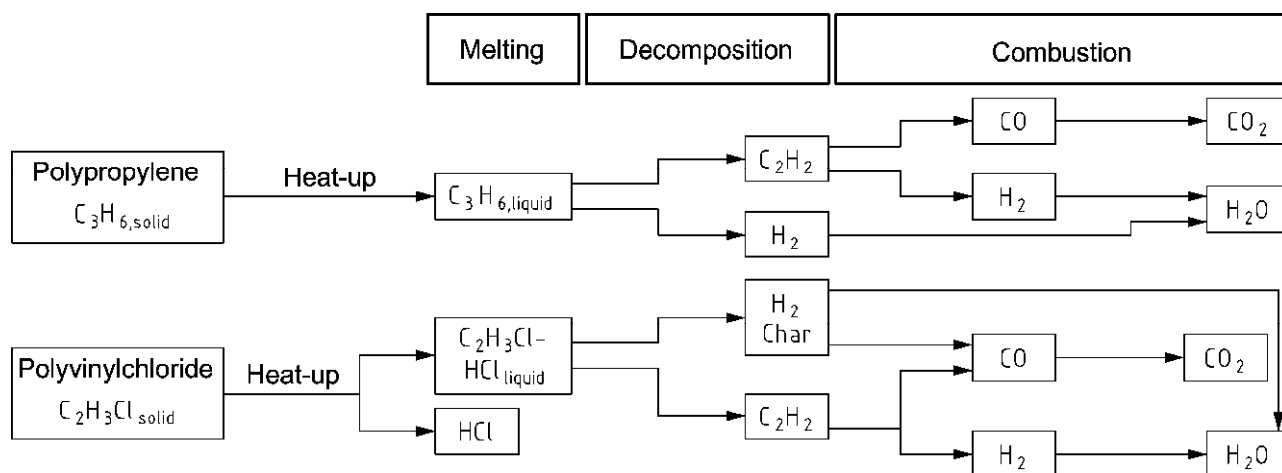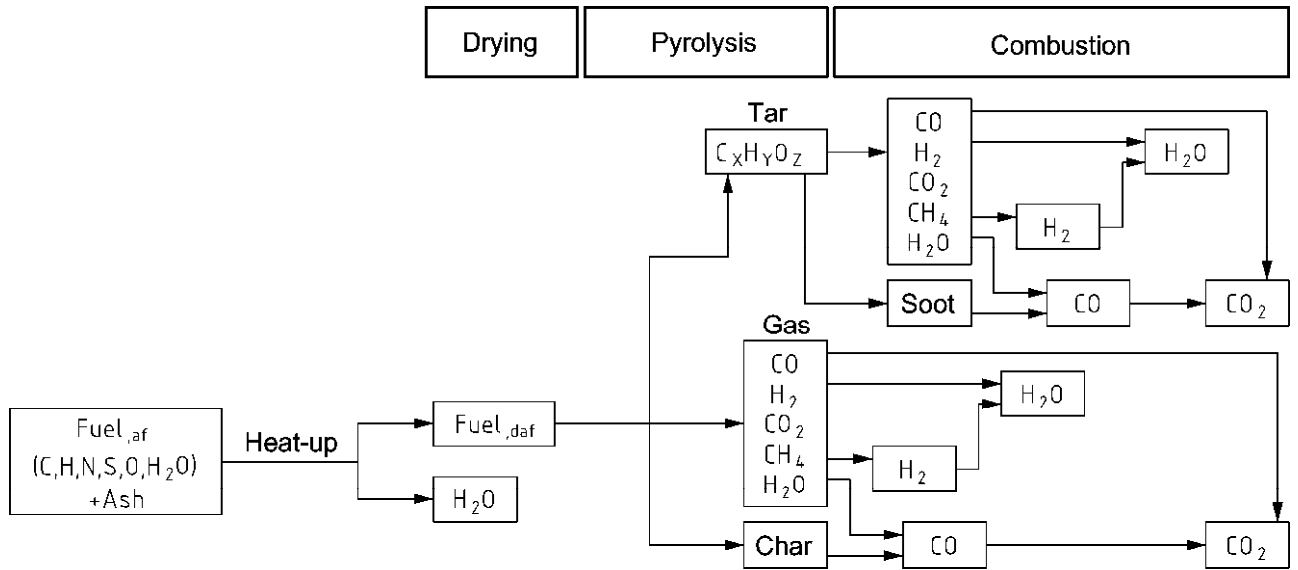

Figure 4 — Plastic combustion model [11]

Figure 5 — Modelled reaction scheme for coal and biomass

The combustion of SRF like any other solid fuel can be simulated by way of adopting and modifying existing modules that have worked for pulverised coal combustion. The three primary phenomena that contribute to the predictions using CFD calculations are chemical reactions, flow behaviour, and heat transfer [12]. Figure 6 shows how such tools have been used to visualise burnout profiles of different SRF particle sizes in a boiler [13]. It shows that the burnout for larger particle sizes ($d_{50} = 5$ mm) were about 0,5 kg/kg$_o$ according to the burnout colour code. Particle tracking has also been performed for coal, the biogenic and the plastic fraction of SRF and it is illustrated in Figure 7.
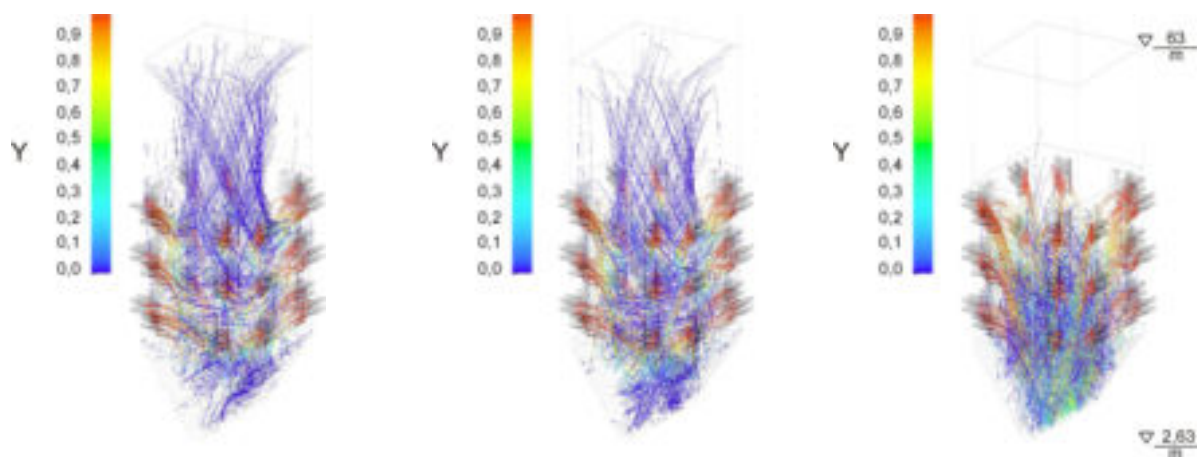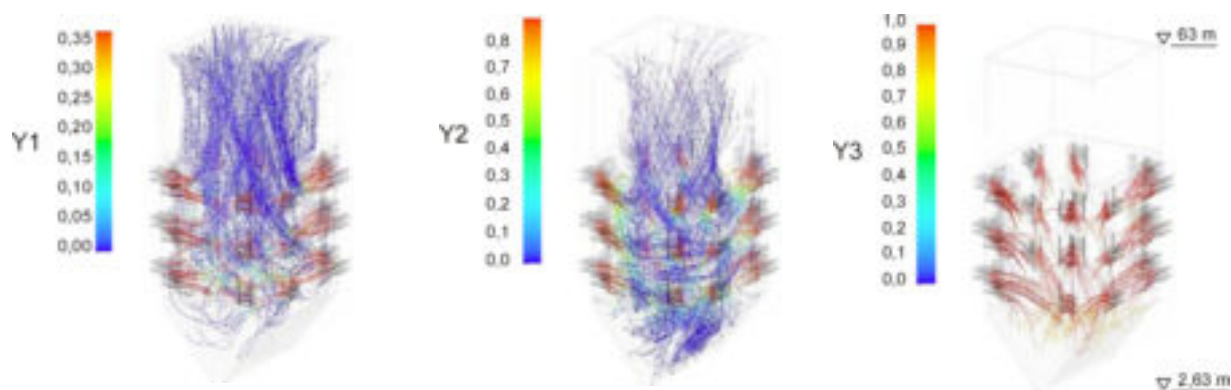
a) **Biogenic fuel, d_{50} = 1,3 mm**   b) **Biogenic fuel, d_{50} = 2,5 mm**   c) **Biogenic fuel, d_{50} = 5,0 mm**

Key

Y   Burnout colour code

Figure 6 — Simulation of SRF burnout in a boiler (see [13])

a) **Coal, d_{50} = 0,13 mm**   b) **Biogenic fuel, d_{50} = 1,3 mm**   c) **Plastic fraction (PP),**
                                                                                        d_{50} = 1,3 mm

Key

Y1, Y2, Y3   Burnout colour codes

Figure 7 — Particle tracks showing the burnout of coal, biogenic and plastic fuel (see [11])

For each case, the particle tracks show representatives of the whole particle spectrum, reproducing the decrease of combustible substances in the particle. The maximum values in the legends refer in case of coal to the initial *daf*-combustible substance, in case of biogenic and plastic to the initial *af*-combustible substance of the particle. In comparison to coal, several differences in the combustion behaviour of the SRF fractions can be observed. Partly they are due to the different particle size distributions, partly to the different behaviour of the fuels themselves. Whereas the fate of the coal and the biogenic particles is characterized by time-consuming de-volatilisation and char burnout steps, the plastic particles undergo a relatively long melting

process followed by a rapid decomposition phase (heat of decomposition is negligibly small), and transform relatively quickly into the gaseous phase.
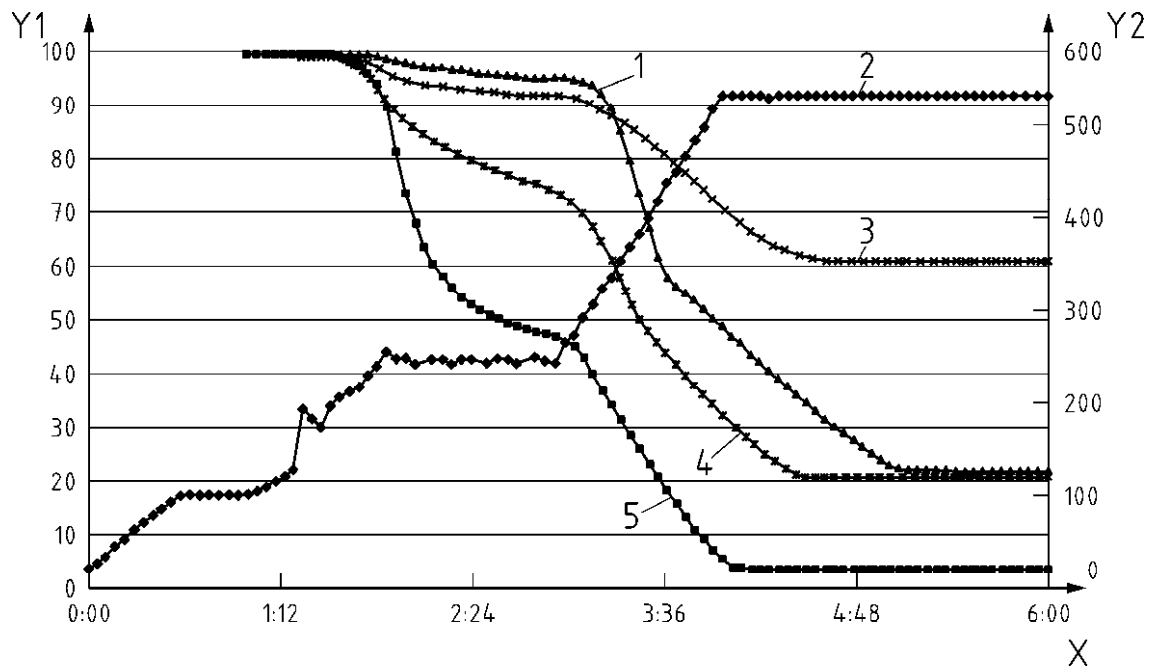
3   Thermal gravimetric analysis

Different methods and apparatus such as thermo-gravimetric analysis (TGA), differential thermo-gravimetric analysis (DTG), high temperature wire mash (HTWM), and laboratory-scale batch reactors (drop tube furnaces etc.) are used to determine kinetic data (see [6], [14]). Most of the apparatus dealing with single particles, offers the ability to investigate kinetic properties of major fuel particle fractions, such as plastic, paper, wood, etc. However, a transfer or prediction of how the real fuel mixture behaves is more difficult. In this context, the requirements for sampling and sample reduction needs to be emphasised as TGA and comparable laboratory test methods usually operate with very low sample amounts (milligrams to grams) [15]. To gain reliable results, similar effort is required to prepare test portion just like in the case for standardised chemical and physical test methods.

The most used technique in thermal analysis involves continuously measuring the physical or chemical change in the substance whilst it is being subjected to a controlled temperature programme. The measured variable may be the change in weight, temperature or dimension of the substance, the flow of heat into or out of the material, or some other quantity. Three techniques will be reviewed as these can be combined into one instrument enabling more extensive information to be derived. The emphasis will be on themogrametric methods where the measured variable is the change in weight of the sample.

The apparatus used for thermogravimetric analysis may be operated in the following modes, although the first one is not always present:

1) differential thermal analysis (DTA) in which a small quantity of pulverised fuel (typically 10 mg to 20 mg) and a thermal inert reference material are separately heated in an electric tube furnace at a controlled rate in a given atmosphere. The temperature difference between the sample and the inert material is continuously measured with a differential thermocouple pair and plotted as a function of furnace temperature. The curve obtained is sometimes called the combustion curve;

2) thermogravimetric analysis (TG) in which a small quantity of the powdered sample is heated on a highly sensitive microbalance in a given atmosphere, either in an isothermal or in a non-isothermal mode with pre-set rate of temperature rise. The change in weight of the sample is measured and plotted as a function of the furnace temperature or time. TG is mainly used for composition analyses of solid fuels to determine the temperature ranges of weight changes and to investigate char burnout;

3) derivative or differential thermogravimetric analysis (DTG) which is similar to TG except that a continuous plot of the rate of weight loos with time as a function of furnace temperature is produced. When the solid fuel is heated in an atmosphere of flowing air, the graphical plot produced is generally known as the burning profile curve. If the furnace atmosphere is an inert gas (e.g. N_2), the curve is called volatile release profile. DTG analysis provides a „finger print" of the complete combustion process of solid fuels. The burning profile produced can provide a comparative evaluation of the combustion characteristics of the SRF in different firing systems, i.e. the behaviour of a new fuel can be assessed by comparison with well-known solid fuels (coals). The volatile release profile yields information on the mode of breakdown of the organic substance as it is heated.

TG, DTG and DTA are empirical techniques. Consequently, all results are dependent on the test conditions and apparatus, all well as the characteristics of the solid fuel. Different devices are available on the market. The method is reliable and reproducible. The determination of kinetic data and classification numbers is possible. As the method is restricted to relatively low temperatures and moderate heating rates, the results cannot be directly transferred to full scale processes. Low sample quantities require a homogenous sampling and sample reduction. Figures 8 and 9 show respectively the results of TGA/DTG analyses of different SRF and the different behaviour regarding volatile release and combustion. Figure 10 shows the proximate analysis of coal from a TGA.
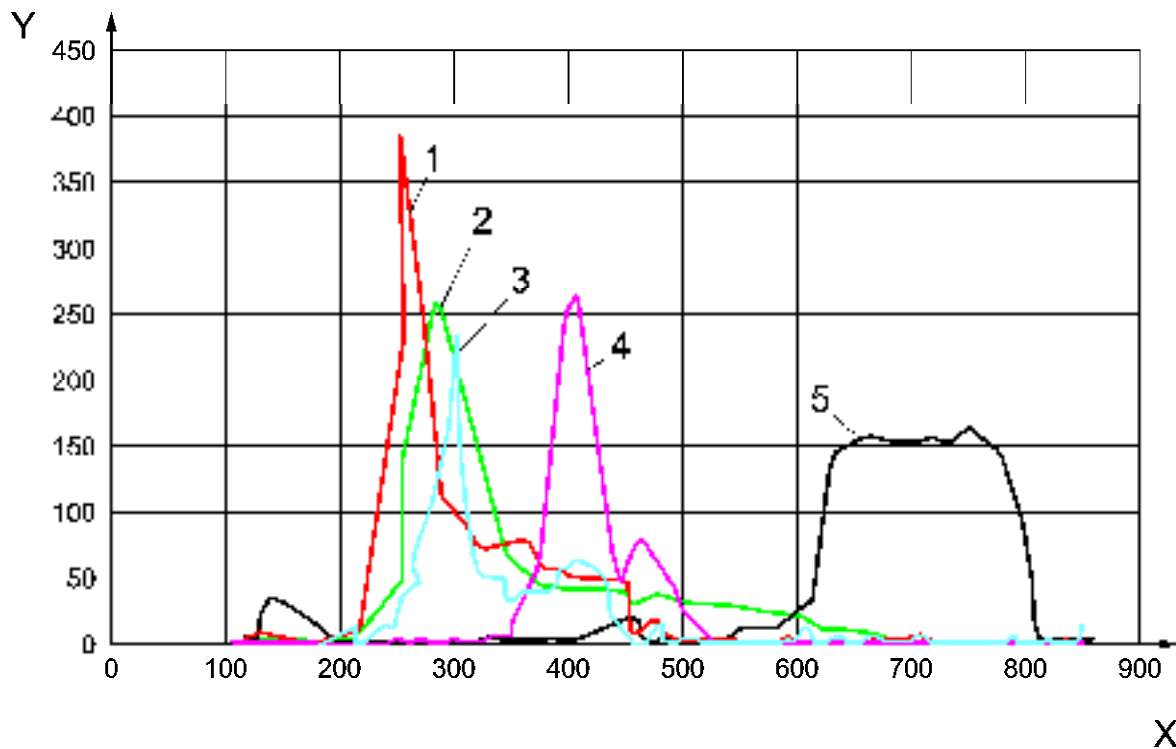
Key

Y1   Mass fraction in percent
Y2   Temperature in degrees Celsius
X   Time in hours
1   Shredded tyre
2   Temperature
3   Sewage sludge
4   Paper/plastic
5   Demolition wood

Figure 8 — Burning profiles of SRFs in thermo-gravimetric analyser
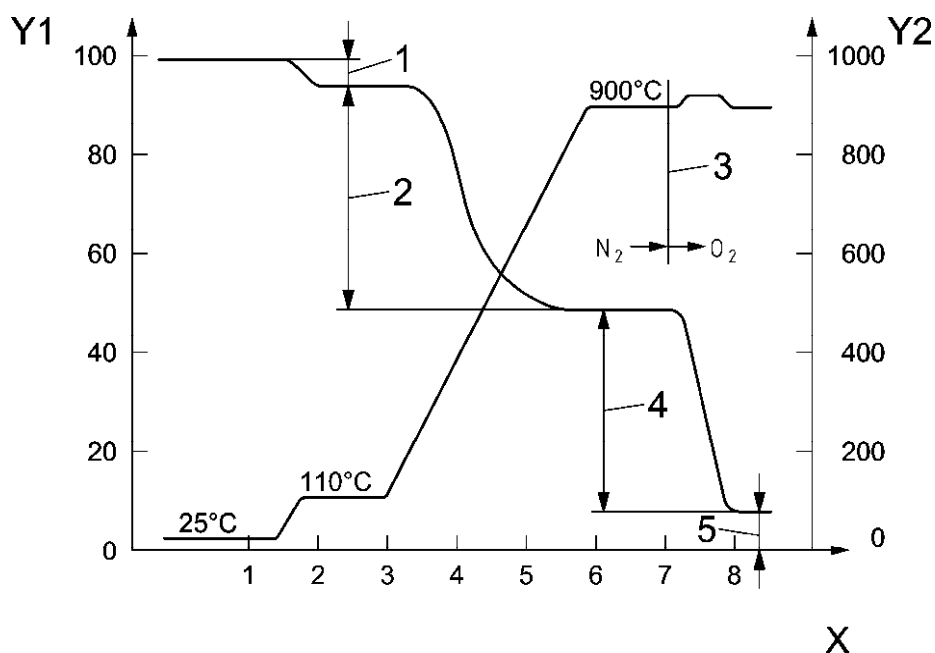
Key

Y   Change in mass per time unit (dm/dt)
X   Temperature in degrees Celsius
1   SRF (high biomass share)
2   Natural wood
3   Newspaper
4   Polyethylene terephthalate (PET)
5   Fixed carbon

**Figure 9 — DTG results of different fuels with peaks showing
maximum thermal decomposition temperature)**

Key

Y1   Sample mass in percent
Y2   Temperature in degrees Celsius
X   Time in minutes
1   Moisture in percent
2   Volatile in percent
3   Atmosphere change
4   Fixed carbon in percent
5   Ash in percent

Figure 10 — Schematic TG curve showing proximate analysis of coal (see [16])

TG/DTG can provide:

— a proximate analysis of SRF;

— a comparative evaluation of different SRF burning profiles;
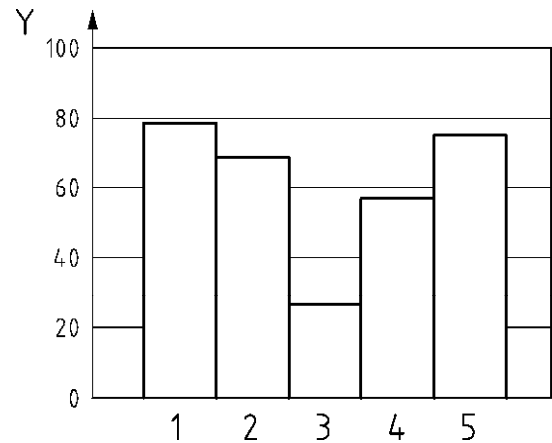
— kinetic data;

— information over all the whole combustion process.

However, TG/DTG:

— does not simulate PF boiler conditions or FBC;

— is restricted to relatively low temperature operation and low heating rates;

— data interpretation can be difficult.

It can be summed up, although with some reservations, that the TG/DTG is reproducible, is repeatable, is relatively fast, can be automated and are readily available in most fuel laboratories.

Tests were made to compare the method as specified in CEN/TS 15402 [17] for volatile matter with a TGA analysis. The results are shown in Figure 11 and the differences between the methods are negligible.
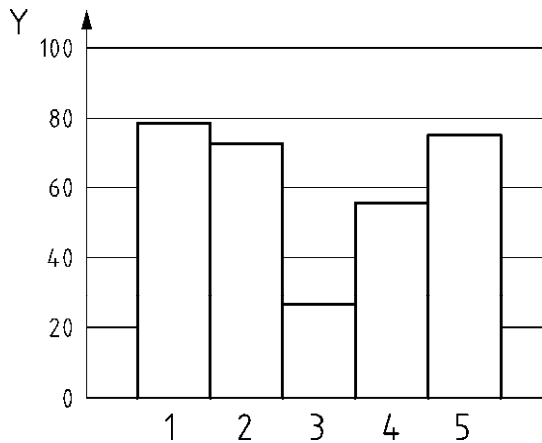
a) Results obtained in accordance with CEN/TS 15402

Key for a)

Y   Volatile matter in percent
1   SRF with a volatile content of 79,41 %
2   SRF with a volatile content of 72,76 %
3   SRF with a volatile content of 26,83 %
4   SRF with a volatile content of 55,20 %
5   SRF with a volatile content of 75,17 %

b) Results obtained according to an instrumental thermo-gravimetric analysis (TGA)

Key for b)

Y   Volatile matter in percent
1   SRF with a volatile content of 78,82 %
2   SRF with a volatile content of 69,11 %
3   SRF with a volatile content of 27,05 %
4   SRF with a volatile content of 57,21 %
5   SRF with a volatile content of 75,06 %

Figure 11 — Comparison between the method specified in CEN/TS 15402 [17] (a)) and an instrumental thermo-gravimetric analysis (TGA) (b))

4   Standard fuel analysis

4.1   General

The basic information on SRF regarding the physical, mechanical, biological, and chemical properties can be determined using the methods developed and or adopted in the frame work of CEN/TC 343. These basic information do not necessary predict the combustion behaviour but are vital in the evaluation of the fuel quality. These methods are shortly described in Clauses 4.2 to 4.6.

### 4.2   Proximate analysis: Moisture, volatiles, and ash content

The relation between these parameters determines the start and progress of the combustion process. The methods are described in CEN/TS 15402 [17], CEN/TS 15403 [18], and CEN/TS 15414 [19].

4.3   Ultimate analysis: C, H, N, S, Halogens

The method is based on the complete oxidation of the sample („flash combustion" instruments can also be used) which converts all organic substances into combustion products. The resulting combustion gases pass through a reduction furnace and are swept into the chromatographic column by the carrier gas (helium) where they are separated and detected quantitatively by appropriate instrumental gas analysis procedures (for example by a thermal conductivity detector (TCD)). The samples are held in a suitable container (tin or other crucible) and then dropped inside the quartz tube furnace al about 1 000 °C in an oxygen stream for complete oxidation in the presence of a catalyst layer. Excess oxygen is removed by contact with copper, while nitrogen oxides are reduced to elemental nitrogen. These methods are outlined in CEN/TS 15407 [20] and CEN/TS 15408 [21].

4.4   Gross calorific value (GCV)/net calorific value (NCV)

The calorific value is one of the basic parameter which is determined for all fuel. As it marks the energy content of the fuel its influence on the combustion process is huge. Marzi [22] states that the problem is the relation between the components of the fuel and their contribution to the calorific value. The effort to analyse this proportion in a laboratory is rather big. In general, the GCV will be measured by a bomb calorimeter (see Figure 12); this method is defined in CEN/TS 15400 [23].
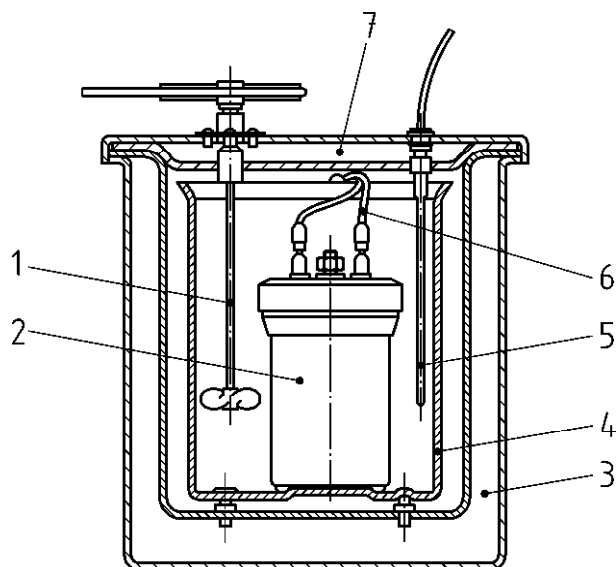
Key

1	Stirrer	5	Platinum resistance thermometer
2	Calorimeter bomb	6	Ignition lead
3	Jacket	7	Jacket lid
4	Calorimeter vessel		

Figure 12 — FTT Bomb Calorimeter

4.5   Particle size distribution

The particle size distribution analysis is also covered under the CEN/TS 15415 [24], where the sieve analysis method is proposed (see Figure 13). However, this method is not suitable for every SRF since some types of SRF, which have varying particle densities and are fluffy in nature, entangle around each other and further agglomerate during sieving. For this reason, a different method which is based on an optical recognition is suggested to deal with this problem.

Figure 13 — Example of sieving equipment

4.6   Ash content and ash melting behaviour

From parameters regarding the behaviour of ash in the combustion process, only the ash melting behaviour is covered by CEN/TS 15403 [18] and CEN/TS 15404 [25]. These parameters are relevant for the combustion as the ash content determines the amount of „inert" material in the process after the combustion and the ash melting affects the behaviour of this material in process. But there exist a variety of methods for ash analysing which are derived from primary solid fuels (e.g. coal) and can be used.

5   Advanced laboratory methods for fuel characterisation

5.1   General

The focus of the advanced analysis is to connect the standard fuel characterisation methods and operational behaviour of the designated process. Figure 14 is an example of an improved fuel classification method that link standard fuel parameters with process parameters. Such process parameters are determined by the so called advanced analytical methods. These methods are developed to determine most relevant fuel characteristics under process related conditions. According to changes in the fuel spectrum and the implementation of new plant technologies, such methods should be individually proven in connection with their applicability and adjusted concerning the requirements and specifications of the new processes and fuels developments. Further classification parameters and methods are published in several papers (see [10], [26], [27]).
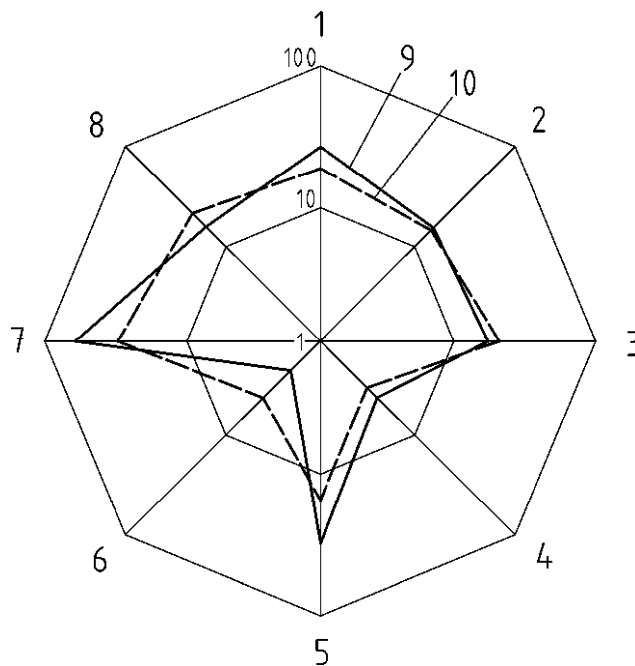
Key

1	Net calorific value	6	Moisture
2	Volatile fuel nitrogen	7	Volatiles
3	Kinetic parameters;	8	Ash
	– char, and	9	SRF 1
	– volatile	10	SRF 2
4	Aerodynamic properties, residence time		
5	Organically bounded alkali		

Figure 14 — Example for SRF characteristics

A very important aspect during characterisation of a heterogeneous fuel is the information about their composition. The basic fuel composition (i.e. plastic, paper, cardboard, textiles) gives a first overview about the components of the fuel which are relevant to the combustion. It also designates in a first step what kind of particles are to be expected, e.g. foils. There is no standard method for the determination of the basic fuel composition and it is mostly done by hand sorting, especially for very heterogeneous fuel streams like SRF produced from municipal solid waste (MSW) (see Figure 15).
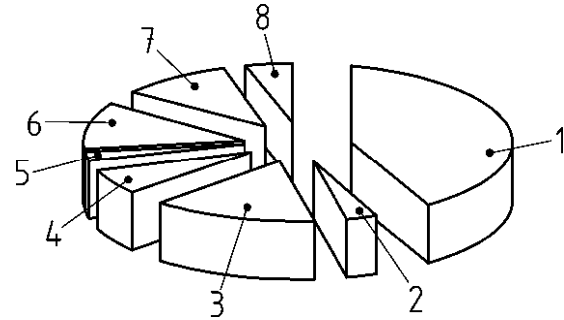
Key

1	Paper cardboard 43 %	5	Foam 2 %
2	Wood 3 %	6	Composite
3	Plastic foils 16 %	7	Textile/Fluff 11 %
4	Hard plastics 8 %	8	Others 5 %

Figure 15 — High calorific fraction (HCF) from municipal solid waste (MSW) and its percentage composition (see [26])

The knowledge of major fuel components and related particle characteristics forms a fruitful basis for the layout of the used test setups and the formulation of a test matrix.

Another approach could be based on investigations with pure fuel fractions which are dominating the combustion process. According to this approach, a transfer of the results to heterogeneous fuels could be successful.

5.2   Determination of fuel composition

The determination and verification of macroscopic fuel components is important to identify critical fractions such as Ferro and non-Ferro metallic materials, inorganic impurities, and other critical components like PVC. Additionally, it could be a useful method to distinguish and quantify major components such as paper, plastic, cardboard, wood, etc., which are relevant components concerning combustion behaviour and amount of biomass content. Beside the hand sorting, optical methods show a high potential to be applicable to most of the SRF. The method under development is highly automated and based on the know-how of organic petrography, and microscope including soft-image technology. Figure 12 shows the microscopic analysis of SRF composition.

Figure 16 — Advanced microscope analytic of fuel composition

5.3 Composition and calorific value of the volatile matter

There is no information about the release of volatile matter at different temperatures and the calorific value of the volatile matter if conventional methods for the characterisation of fuels were used. Therefore, a new method for the characterisation and classification of different fuels was developed by Fraunhofer Institute UMSICHT (see [28]). The main principle of the method is the examination of the release of volatile matter at well-defined temperatures. The results provide information about the nature of the volatile matter released at different temperatures and about their calorific value. Since the combustion process is an interaction of degradation and oxidising sub-processes, the whole combustion process can be examined by a step-by-step view of the sub-processes.

The measuring principle is illustrated in Figure 17. In the first step the sample is degraded under anoxic conditions, the volatile matter are oxidised and the combustion products are quantified. The degradation (step 1) is carried out at different temperatures. The result is a specific „fingerprint" of the fuel which describes the release of carbon, nitrogen and hydrogen containing products from the fuel at different temperatures. The calorific value of the volatile matter is calculated on the basis of the composition. The measurement is carried out with a commercially available elementary analysing system.

Figure 18 shows the calorific value of the volatiles and fixed carbon (C_{fix}) for different fuels. For transferring the measuring values to a grate firing system, a simple model with a stationary temperature distribution in the burning bed is used at first. The fuel passes through different areas with a definite temperature in this simple model. There is a defined release of volatile matter in each segment of the burning bed which depends on the temperature of each segment. The results are also shown in Figure 18.
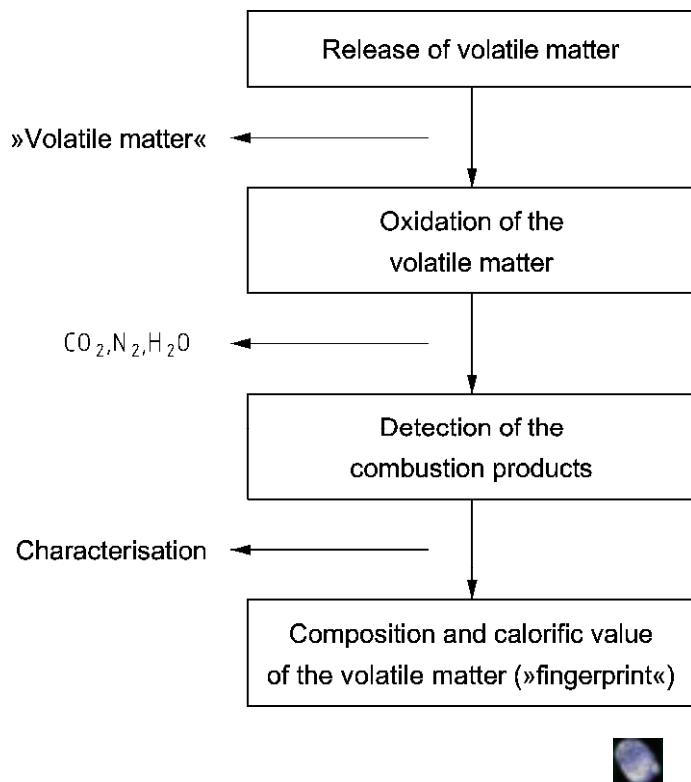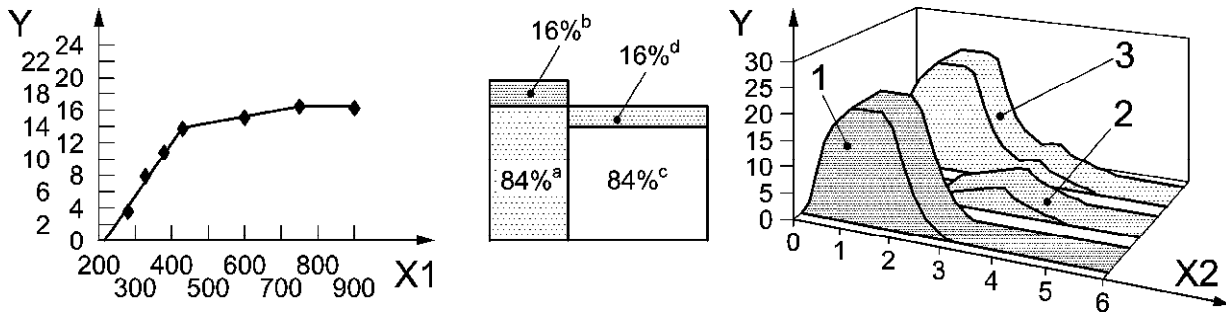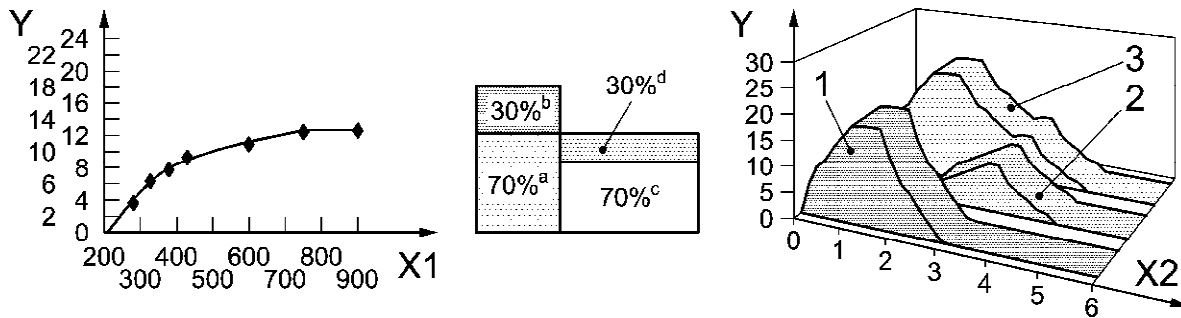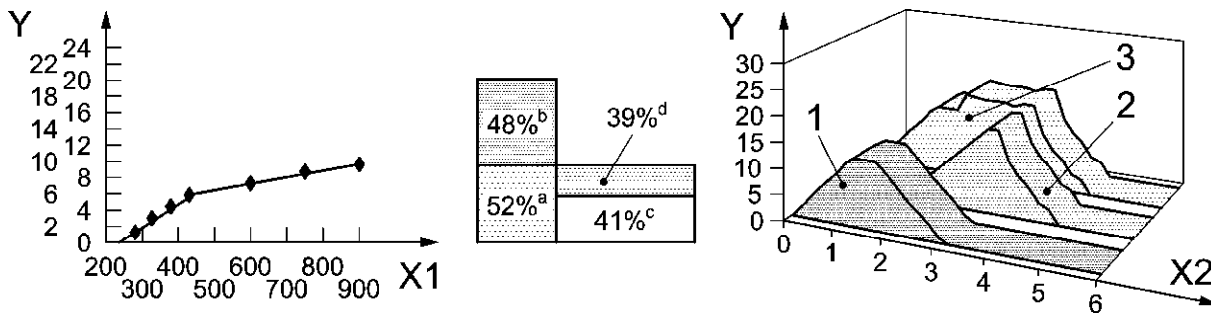
Figure 17 — Principles of the measurement (see [28])

1) **Fuel from industrial waste**

2) **Wood**

3) **Brown coal**

a) **Lower calorific value (LCV) of the volatile matter for different fuels in dependence of temperature:**
HT-Volatiles releases at higher temperatures (> 430 °C),
NT-Volatiles releases at lower temperatures (< 430 °C)

b) **Potential release of high calorific compounds in a grate firing system: The scenario is related to the design of the MARS®[1] plant : feed rate 500 kg/h, residence time 45 min, hold-up combustion chamber 380 kg (all values are related to dry fuel) (see [28])**

Key

Y	LCV in Mega joules per kilogram	a	Volatiles	1	Volatiles
X1	Temperature in degrees Celsius	b	Fixed carbon	2	Fixed carbon
X2	Fuel position on grate	c	LT-volatiles	3	Volatiles + fixed carbon
		d	HT-volatiles		

Figure 18 — Characterisation and classification of different fuels based on the calorific value of the volatile matter

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1) Mars is the trade name of a product designed by Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, Osterfelder Straße 3, 46047 Oberhausen, Germany. This information is given for the convenience of users of this European Technical Report and does not constitute an endorsement by CEN of the product named.

5.4 Kinetic properties

The kinetic data on a fuel provide vital information on the reaction rate and the combustion rate. Major areas of interest are:

— heating of the particle;

— drying and release of volatiles (pyrolysis, devolitilisation);

— ignition and combustion of organic components (volatile combustion);

    — ignition temperature;

    — flame stability;

— ignition and combustion of residual char (char combustion);

    — char burnout time;

    — char reactivity;

    — reactive surface area;

    — particle temperatures.

For experimental determination of kinetic fuel data, many laboratory-scale apparatus are commercially available and are used in different research centres and universities. Examples are thermo-gravimetric analysis (TGA), differential thermo-gravimetric analysis (DTG), high temperature wire mash (HTWM), and laboratory-scale reactors (drop tube furnaces, fixed bed, etc.). Major parameters to select between the different apparatus are the heating rate and required sample amount. In the following some results and schemes of apparatus are shown.

Heated wire grid (HWG) system (also called heated wire mesh): The method can reach temperatures up to 2 000 °C and heating rates up to 10^4 K/s. The used amount of sample is in a range from 2 mg to 15 mg (see[6], [29]). Such a device is shown in Figure 19.
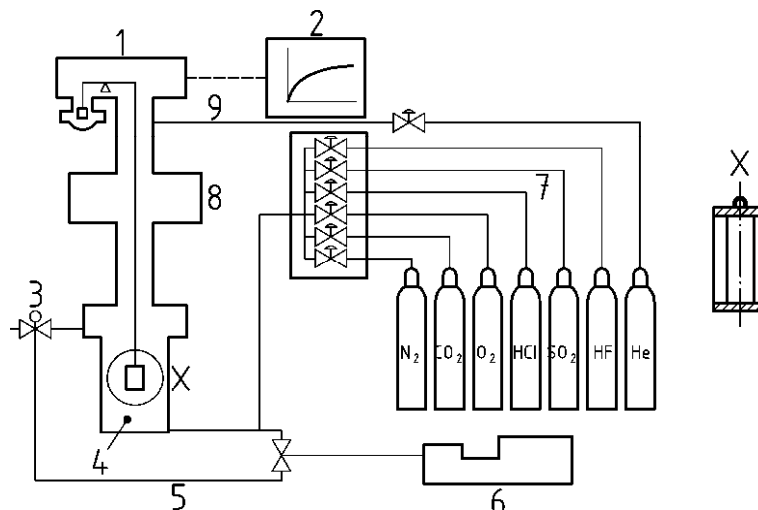
Key

1	Microbalance	4	Reactor
2	Data acquisation	5	Bypass
3	Pressure control valve	6	Steam generator

**Figure 19 — Heated wire grid system and schematic of differential
thermogravimetric analysis (DTA) system (see [30])**

The methods described in this subclause are mostly suitable for smaller particle sizes. For larger particles and sample amounts, an electrically heated oven like the ones shown in Figure 20 can be used. In this case, the time it takes fuel particles to be fully oxidised can be observed and recorded. The particles and samples can be observed by cameras and the released gas concentrations can be analysed by standard analysers, gas chromatography, mass spectrometry, frustrated total internal reflection (FTIR), etc. The experiments can be conducted in ambient air or synthetic gas mixtures. To investigate intermediate combustion steps, char particles can be easily removed from the furnace for further characterisation. The setup (wall temperature in a wide range adjustable) simulates a furnace environment in regards to the particle heat-up leading to de-volatilization, ignition, and char combustion. Investigations with such furnaces are closing the gap especially for the prediction of combustion behaviour and required residence time of large particles > 2 mm used in pulverised fuel fired system; for this approach drop tube furnaces show limitations.
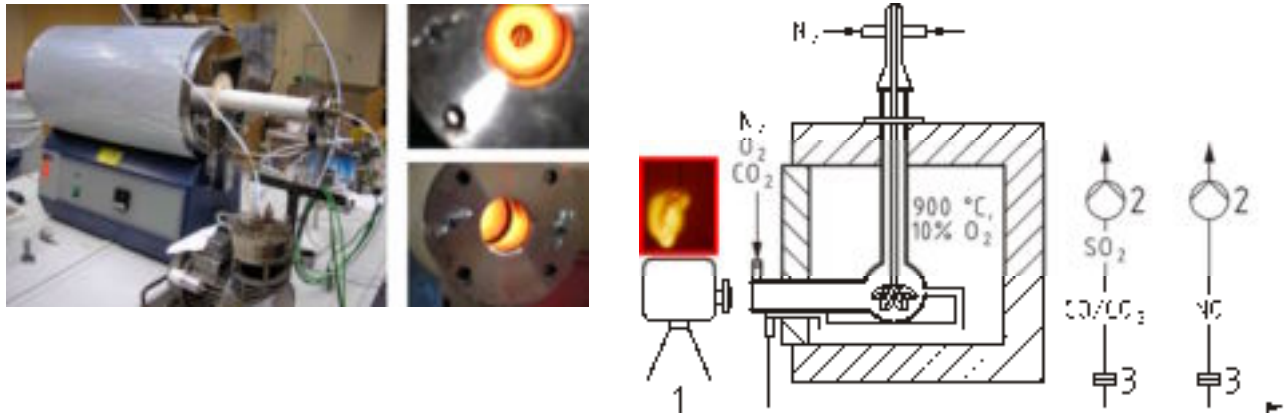
Key

1   High resolution camera
2   Pump
3   Filter

**Figure 20 — Tube furnace and schematic of experimental setups
for particle combustion (see [31], [32])**

The velocity of volatile release can be determined by combining the setup for elementary measurement (see clause 4 and Figure 21) which is usually used to determine the amount of total organic carbon. First of all the volatile matter is released continuously under anoxic conditions in the bottom zone of the furnace. After the release of the volatile matter, the compounds are oxidised in the upper zone of the furnace by copper oxide. An online infrared-measurement of the produced CO_2 is incorporated. The amount of CO_2 versus time gives information about the releasing velocity of the volatile matter. The investigations be done at different temperatures ($T_1 = 300$ °C, $T_2 = 430$ °C, $T_3 = 600$ °C, $T_4 = 900$ °C) (see [28]).
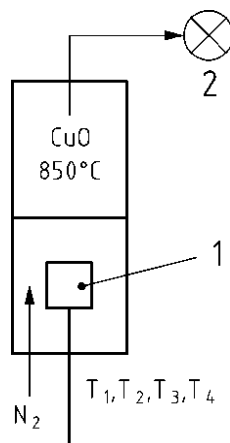

Key

1   Sample
2   On-line CO_2 detection

Figure 21 — Measurement of the releasing velocity of the volatile matter (see [28])

In addition to the methods mentioned above, several others exist at different institutes, e.g. drop tube furnaces (pressurised/atmospheric, see Figure 22), small scale fluidised bed reactors (see Figure 23), and fixed bed reactors (see Figure 24). The drop tube furnaces and fixed bed reactors are designed to approximate the combustion behaviour of pulverised fuel fired and grade fired systems. The determination of kinetic
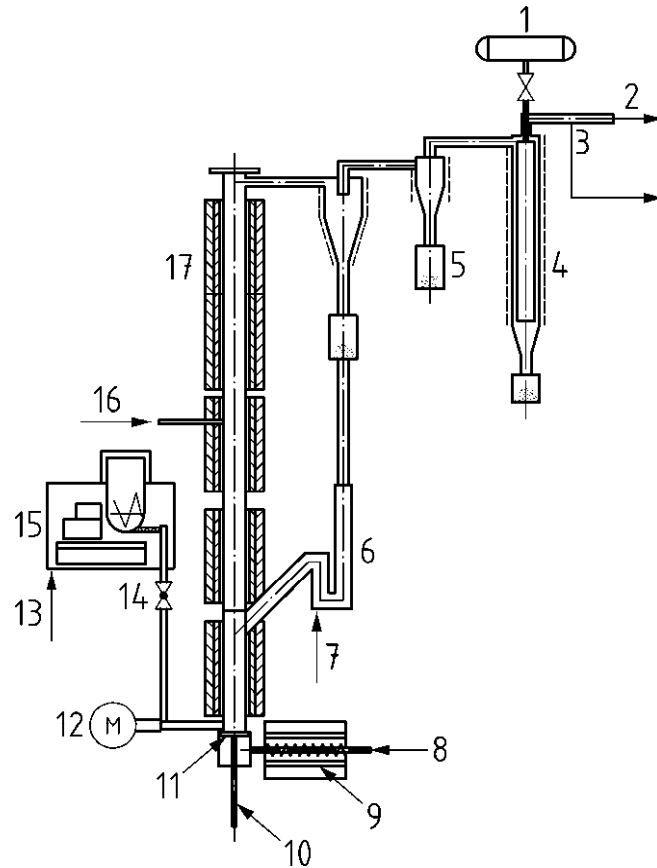
parameters as well as an evaluation of the emission behaviour is possible for pulverised fuels. These reactors are mainly individual prototypes but installed in several research institutions.
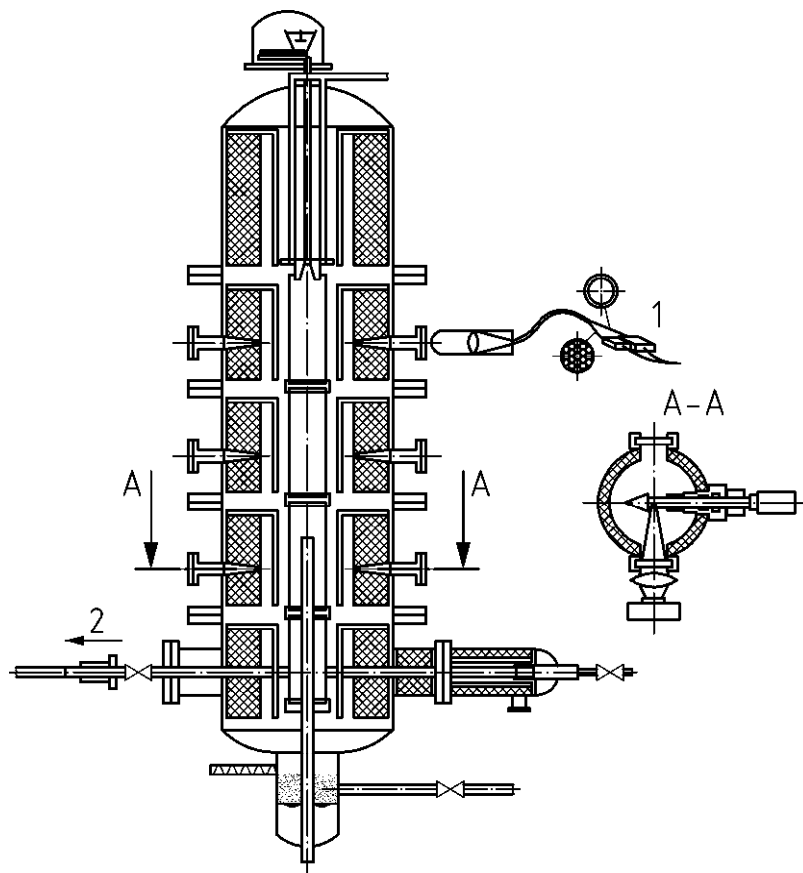
Key

1   2-colour pyrometry
2   Gas analysis
A–A   Alkali detector ELIF

Figure 22 — Atmospheric and pressurised drop tube furnace [34]

Key

1	Pulse cleaning	10	Bed material withdrawal
2	To stack	11	Distributor plate
3	Gas analysis (CO, CO_2, O_2, NO_x, SO_2, N_2O)	12	Fuel feeding
4	Filter with ceramic candle (heated)	13	Feeding air
5	Cyclones (heated)	14	Scale
6	Return leg	15	Screw dosing unit
7	Return leg, fluidization air	16	Secondary air
8	Primary air	17	Five heating zones (3,6 kW each)
9	Electric preheater (3,6 kW)		

Figure 23 — Bubbling and circulating fluidised bed reactor (see [27])
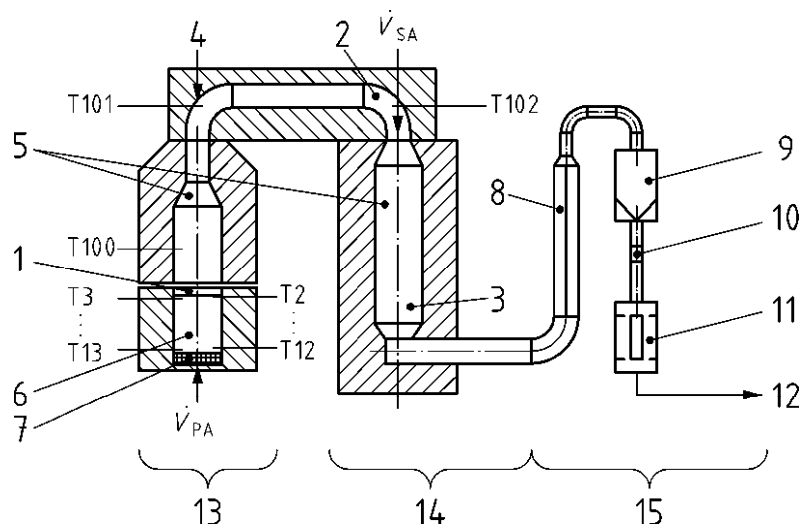
Key

1	Gas sample 1	9	Filter chamber
2	Gas sample 2	10	Venturimeter
3	Gas sample 3	11	Cole adsorber
4	Camera	12	Blower
5	Electrically heated ($T_{max} = 1\,100\,°C$)	13	Burning chamber
6	Fixed bed (volume 10 l)	14	After burning chamber
7	Sample mass recording	15	Flue gas cleaning
8	Heat exchanger		

Figure 24 — Fixed bed reactor [33]

The methods and apparatus shown above can be used to investigate single or combined relevant parameters. To get a full picture regarding combustion behaviour and emission formation the residues and intermediates, such as char and ash, need to be characterised by the standard methods (ultimate, proximate, LHV). Additional methods to determine, e.g. pore structure, are also needed.

According to such analysis results can be correlated regarding several approaches including heating value, composition of released volatiles, remaining chars, release of volatile nitrogen, etc. Such correlations give fruitful fingerprints to characterise a fuel and single fuel fraction concerning ignition, NO_x formation, and reduction potential. The use of synthetic sample with known composition may be an idea to study the influence of one component on the other. Similar approach was used to determine whether significant interactions between single components take place during thermal degradation (see [35]).

Some applications like the laboratory-scale furnaces can also give very good results regarding ash formation by characterising the intermediates and residues by SEM-EDX/WDX, CCSEM, XRD, XRF etc.

5.5 Image analysis method for particle size distribution

Another class of particle size analysis method is based an optical recognition program; here a digital photo of the SRF is used to determine the particle size distribution. There are several available commercial software using such principles to analysed size distribution (see [26]). The main advantage of this method over sieve analysis is that the sizes are determined according to the maximum projection area of the particle. Figure 25 gives a visual expression of the translation process (see [36]).
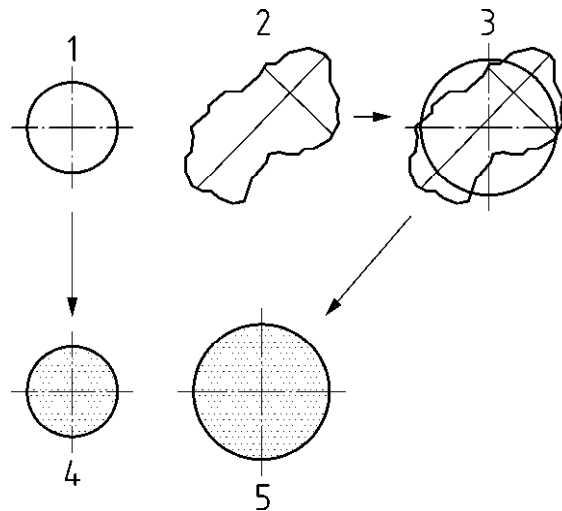
Key

1   Regular circular object
2   Irregular object
3   Circle of an equivalent surface area
4   Sphere of the same projected area like that of regular circular object
5   Sphere of the same projected area like that of irregular object

Figure 25 — Translation of an irregular object (SRF particle) to an equivalent diameter (see [36])

Particle image analysis method (PIAM) classifies particles according to any of the following parameters:

—   equivalent diameter of particle;

—   maximum projection area of particle;

—   major and minor axis lengths of particle;

—   eccentricity (shape and form factor); it is the measure of the circularity of a fuel particle where the factor ranges between 0 and 1, the former represent a rod-shaped whiles the latter shows a circular-shaped particle.

Figure 26 shows the size analysis of high calorific fraction from MSW based on sieving and particle image analysis method (PIAM, see [26]). It is recognised that, particle sizes are down graded using a sieving method. This is because larger particles depending on their shape can go through the sieve when properly oriented to the sieve aperture. In this case, the size distribution is skewed towards smaller fractions. This problem does not exist in image analysis. The primary difference between sieve analysis and PIAM is that, the former is largely influenced by the individual particle weight whereas the later is solely based on the largest projected area of a particle and its frequency in a given sample.
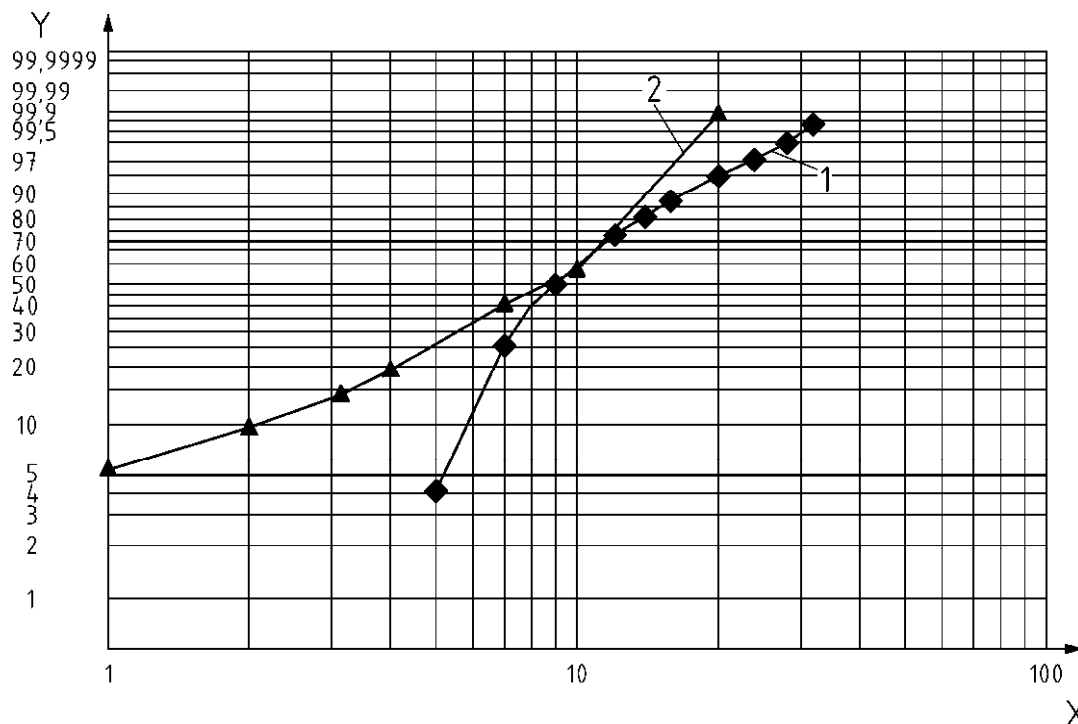
Key

Y   Percentage of particles passing by sieve analysis respectively PIAM
X   Particle size in millimeter
1   SRF: high calorific fraction from municipal solid waste, PIAM
2   SRF: high calorific fraction from municipal solid waste from sieve analysis

Figure 26 — Comparison between sieve analysis and particle image analysis method (PIAM) (see [26])

PIAM touches on a relevant question when charactering SRF where the shape and form of individual fuel particles vary strongly. The particle size and shape is expected to strongly affect the behaviour of the particle in any kind of furnace and is a crucial input value for example when doing modelling of combustion system based on computational fluid dynamic (CFD) calculations.

5.6   Apparent densities of particles and intermediates

The apparent densities of particle and char are necessary in terms of theoretical estimation of particle settling velocity. Some selected SRF particles and chars exposed in a furnace at 1 200 °C and 4 s were analysed; the results are shown in Figure 27.
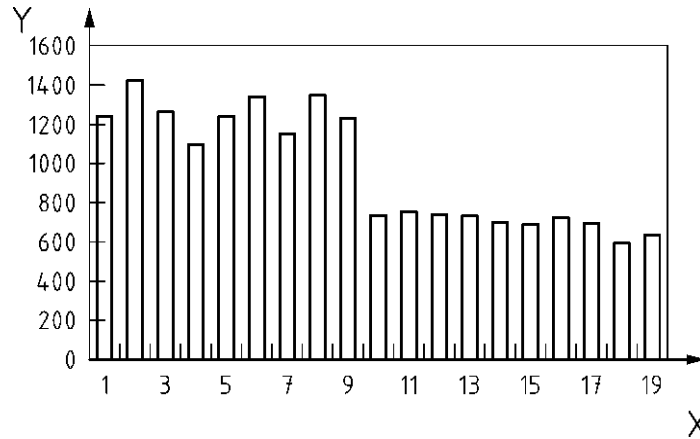
Key

Y   Apparent density in kilogram per cubic meter (kg/m^3)

X   Sample number; No. 1 to 9:   raw particles,

                     No. 11 to 19: char

Figure 27 — Apparent densities of selected particles and char

5.7 Aerodynamic lift velocity

The aerodynamic properties of the SRF particles are characteristic parameters that are used to describe the ability of SRF to be fully suspended in air. This parameter though determined at room temperature gives an estimation of the volume stream velocity that will prevent particles from sudden drop to the bottom ash tray if they are to be co-fired in a pulverised firing system. The set-up involves a fall column as shown in Figure 28. A particle is dropped on the mesh and the flow rate needed to just lift the particle is recorded. The aerodynamic lift velocity (ALV), which is defined herein as the velocity of air in the fall column required to create the lift force necessary to just suspend the particle above the mesh, is then calculated. The method could also be used to characterise intermediates (chars), if the chars show a certain mechanically stability.
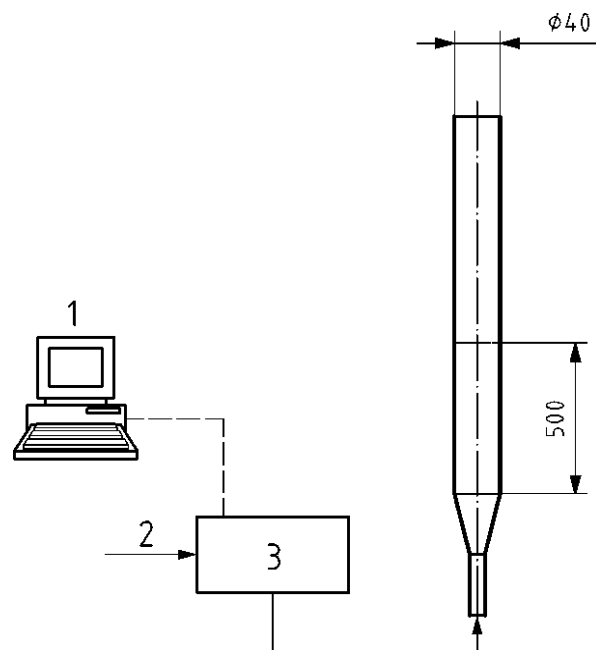
Key

1   Data logger
2   Air flow
3   Flow meter

Figure 28 — Set-up for aerodynamic classification [30]

These ALV numbers can be adopted as a classification number to represent the aerodynamic properties of SRF. This number can be used to prediction for example the burner levels at which the SRF should be injected and whether or not they will plummet or blown pass the combustion zone or whether a complete combustion will be achieved under full load or partial load conditions. The ALV is compared with the volume stream condition of the intended boiler thereby enabling the power plant operator decide the success of the co-firing.

5.8   Slagging and fouling behaviour

Classification numbers, comparable to those used for coal, can generally be adopted to evaluate the slagging and fouling behaviour of SRF. Nevertheless as experiences show, the transfer of such classification numbers, especially if they are derived from ashes produced under conditions which are not similar to the real process conditions is limited. A first valuable prediction of operational problems such as slagging, fouling, formation of fine particles, and corrosion should base on ashes produced in bench-scale apparatus under conditions which are comparable to the final full-scale application. Data published for solid biomasses can in many cases be transferred to SRF because large fractions of this fuel are of biogenic origin. Useful advanced methods to characterise additional fuel parameters relating to slagging, fouling, formation of fine particles and corrosion are:

—   chemical fractionation (see [33]);

—   ash sintering (see [31]);

—   metallic aluminium test method (see documents of CEN/TC 343), etc.

Beside these methods, the fuels and ashes should be analysed concerning elemental and mineral composition. The analysis should not be limited to bulk compositions but be extended to cover single particles for detailed information.

For the development and successful implementation of particle combustion models into combustion predicting tools, such as CFD models, kinetics of the fuel and specifically char kinetic data are of great interest (see [38]). Different methods and apparatus are used to determine kinetic data but the method which apply pulverised fuels are somewhat not applicable to SRF, which are in the size range of 5 mm to 30 mm. What is often done is to mill the SRF to the micron range size before determination. The obvious set back in this approach is that the reactivity of pulverised SRF is totally different from raw SRF. A new approach to deal with large particles is therefore necessary.

6 Operational behaviour in the combustion process

The combination of standard and advanced methods including bench-scale tests offer a profound basis to evaluate the behaviour of a new type of fuel. The acquired data are important and will improve results from sub-models which can further be implemented in CFD codes such as AIOLOS, FLUENT (see [2]), etc.

Nevertheless some limitations are left concerning a reliable transfer to a full-scale application by the above mentioned methods and there combination. According to the known risks by using a new type of fuel where the plant was not designed for. The next required steps for a successful implementation are tests in a semi-technical or pilot scale plant (see [15], [39]). Such investigations deliver further substantial information covering the whole process chain from fuel preparation, feeding, combustion to emissions and utilisation of residues. Pilot-scale test are more expensive than standard and advanced fuel characterisation methods but in comparison to the risks and costs associated with unsuccessful full-scale, test trials cost are marginal.

A promising approach for laboratory-based methods is the utilisation and comparison with reference substances. For semi- to pilot-scale investigations specification and comparison with a reference case is required. Reference cases should be defined in close cooperation with the individual plant operators.

Several research institutions are equipped with pilot-scale combustion facilities, including pulverised-fuel, fluidised bed, grate fired systems (see Figures 29, 30 31, etc. and [15], [22], [39]). The idea is to match the real power plant process as far as possible with the main advantage to transfer the results to the specific firing system. They are also suitable to investigate the corrosion and slagging/fouling potential under most realistic combustion conditions. If they are equipped with a real flue gas path the evaluation of the effects on flue gas treatment is possible. Nevertheless pilot-scale facilities are commercially not available. The demand of time and personnel is considerable low in comparison with full scale tests.

As SRF can be classified as difficult fuels (see [10]), the tests can give answer to critical aspects such as:

— possible interaction between coal dust and plastic particles;

— insufficient particle burnout due to a reduced heat transfer as a result of particle transparency or aluminium coatings;

— unpredictable residence times as a results of irregular-shaped particles;

— emission behaviour of the process (chlorine, heavy metals);

— influence on and quality of combustion residues (fly and bottom ashes, flue gas desulphurisation (FGD) products);

— corrosion potential;

— slagging and fouling behaviour;

— deactivation/contamination of catalyst (DeNO$_x$);

— capacity reduction of electrostatic precipitator (ESP);

— formation and emissions of fine particles.

The pilot and large scale experiences have shown that a transfer to other combustion technologies is rather limited and requires a profound expertise. Even a transfer to another plant with comparable technology is restricted. Each plant has its own technical and operational characteristic and operates with a particular fuel profile and also every country is unique in terms of regulatory control and promotion schemes. According to these boundary conditions a successful large-scale implementation of a new fuel would require a profound case by case testing based on the four-step procedure as described in this report. The following are some examples of pilot test facilities which are used to investigate co-incineration and mono incineration applications by using different combustion technologies such as pulverised fuel, fluidised bed and grate firing systems:
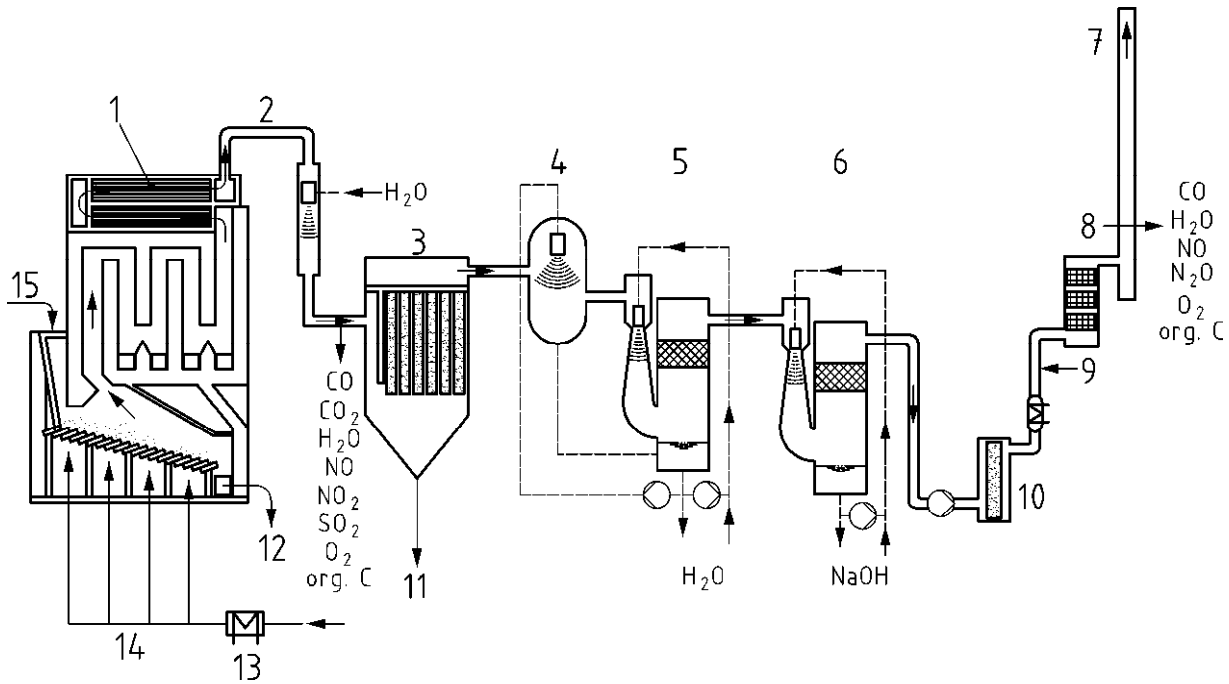
Key

1	Boiler	9	Ammonia liquor
2	Prequench	10	Adsorber
3	Bag filter	11	Fly ash
4	Quench	12	Slag
5	Scrubber 1	13	Preheater
6	Scrubber 2	14	Air
7	Stack	15	Waste
8	Selective catalytic reduction		

Figure 29 — Grate firing system (TAMARA) (see [33])
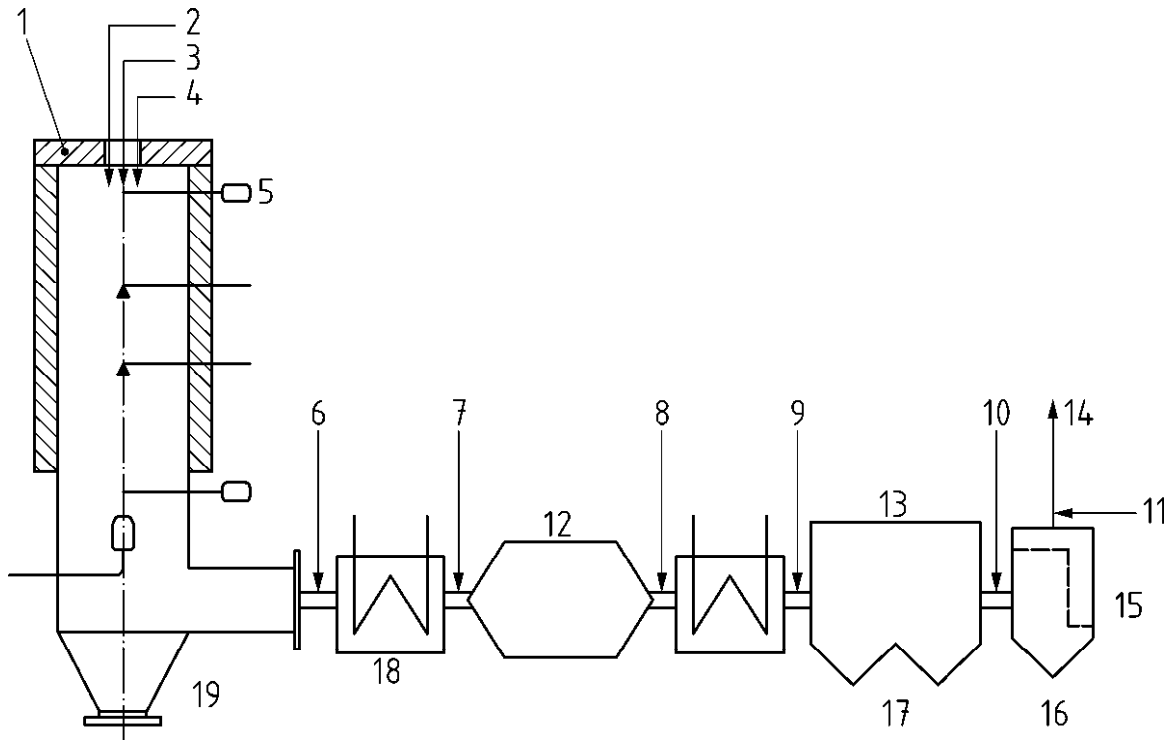
Key

1	Burner	11	Sample point 6
2	Coal + primary air	12	SCR catalyst
3	Additional fuel + conveyor air	13	Electrostatic precipitator
4	Secondary air, flue gas recirculation	14	To stack
5	Vertical furnace	15	Fabric filter
6	Sample point 1	16	Fly ash (one fraction)
7	Sample point 2	17	Fly ash (three fractions)
8	Sample point 3	18	Fly ash (one fraction)
9	Sample point 4	19	Slag and ash (d > 100 µm)
10	Sample point 5		

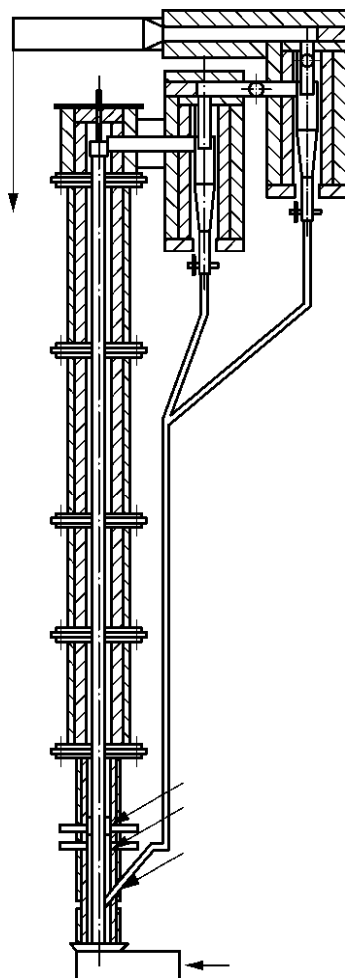**Figure 30 — 500 kW pulverised fuel combustor (see [15])**

Figure 31 — 100-kW CFB reactor (see [39])

7   Summary

The wide fuel band under SRF, from MSW to shredded tyres to demolition wood, causes difficulties to manage on a specific test method to determine the combustion behaviour. There are many important aspects of SRF that need to be known in order to predict the character of the fuel. Choosing a single parameter which covers all the combustion processes is hardly to accomplish. However, one approach would be to define the parameters that need to be measured at each stage during combustion. There are already methods in use which provide promising results as outlined in this report. The schematic approach as summarised in Figure 2 can be the bases to characterise SRF of different qualities. In this regard, certain expertise would be needed to select and combine most promising characterisation methods and test setups with close correlation to the intended combustion application. First and foremost, a standard analysis should be performed on any given SRF after which the so-called advanced analysis can be performed following the selection of the type of combustion system.

Burning profiles in TGA/DTG analysis can effectively be used to compare different SRF. Several characteristic temperatures can be derived from the profiles and the relation from one fuel to the other can be achieved. These include maximum degradation temperature, ignition and peak burnout temperatures. For the results to be directly comparable, the TGA/DTG tests should be conducted under identical operating conditions and, ideally, with the same instrument. The only doubts about the method are that fact that conditions in the TGA/DTG do not simulate those in real boilers. Therefore, it is difficult to translate data or their real meaning into conditions of large scale plants.

Semi-technical and pilot scale plants are seen as an important step in the process to determine the combustion behaviour of SRF. It afford the ability to evaluate the effect of the fuel in all aspect of plant operation, flue gas cleaning assessment, slagging and fouling and the total plant efficiency. The combustion data derived from such plants are to a higher extent transferable to similar large scale plants. The kinetic data derived here also improve the predictions obtained by computation calculations.

The so-called advanced methods are essential to provide insight on the performance of SRF during combustion in a selected firing system. They can help to provide answers such as the burnout time, aerodynamic behaviour pertaining to whether the SRF particles will plummet into the bottom ash or blown pass the combustion zone, and also the possible travel distances of fuel particles before they are completely consumed. These and many other answers to empirical questions can be handled.

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