SEWAGE SLUDGE FROM WASTEWATER TREATMENT AS ENERGY SOURCE

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Abstract

Increasing urbanization and industrialization cause to an enormous increase of wastewater all around the world which requires modern wastewater treatment plants [1]. Today such wastewater treatment plants are highly efficient and eliminate more than 98% of the chemical and biological contaminants and pollution. This pollution is subsequently accumulated in the sewage sludge, the by-product of wastewater treatment plants. In the past, the most sewage sludge produced throughout the world was disposed in 4 ways; spreading on farm land as fertilizer, landfill, ocean dumping or combustion. All these methods are discussed controversial, but since disposal routes like ocean dumping, landfill and even agricultural use are already banned in many countries the energetic utilization will become more and more important in the future. The following paper is focused on the transformation of sewage sludge into useful energy by efficient and environment friendly combustion processes.

Keywords: Integrated Water-Resource Management, Sewage sludge, Conversion Technologies, Combustion

Introduction

Sludge pre-treatment

Sludge, produced in conventional wastewater treatment plants has usually only 2 – 8 % dry matter content. Because of the high amount of organic matter (up to 60% on a dry basis [2]) anaerobic digestion to produce biogas is the most common 1st treatment step. Biogas is a valuable renewable energy source, contributing to the substitution of natural gas and the reduction of anthropogenic greenhouse gas emissions. For the production of biogas from sewage sludge conventional mesophilic (T 25 – 40 °C) wet fermentation processes are suitable. Typical retention time for the sludge in the anaerobic digester amounts to approximately 20 days [2]. The produced biogas is a mixture of gases that is composed mainly of methane (CH_4): 40-75 vol.% ; carbon dioxide (CO_2): 25-55 vol.% and other gases like hydrogen or hydrogen sulfide; 1-5 vol.% and can be used in internal combustion engines for the combined heat and power production.

In conventional anaerobic digesters and under mesophilic conditions, only about 20 to 30 % of the organic matter will be transferred into biogas. On the other hand, the remaining organic matter and nutrients suggest that the sludge could be a promising fertilizer in agriculture, but because of the presence of heavy metals like Zn, Pb, Cu, Cr, Ni, Cd, Hg and other toxic components, disposal on farm lands is often unacceptable. The combustion of the organic components, associated with the thermal inertization of the inorganic elements in the ash is a promising disposal opportunity. An innovative combustion Technology for sewage sludge particles in a spouted bed cascade system was developed at the Berlin Technical University and will be introduced.

Fuel characteristics

Incineration of sewage sludge requires that the heating value is sufficient for an appropriate combustion process (LHV > 4.5 MJ/kg). Because of the relation between water content and heating value (see figure 1), a drying process is necessary as a pre-treatment step.

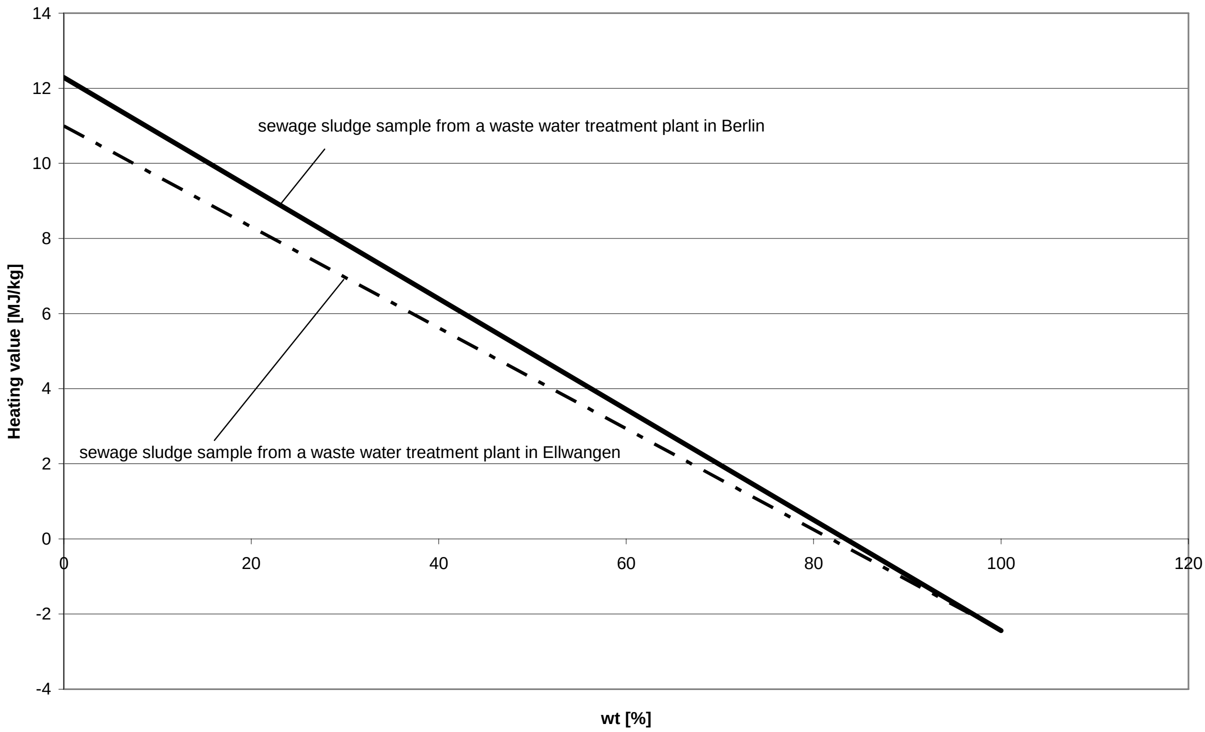

Fig 1. Relation between heating value and water content of two exemplary sludge samples

The dewatering of sewage sludge can be attained by mechanical and thermal processes [3]. The free water can be separated by mechanical dewatering processes, but such processes are usually limited to a sludge with a total solids content as low up to 40%. Figure 1 shows that the heating value of such sludge is still very low and combustion may be difficult. At the Technical University of Berlin in 2001, altogether 27 sewage sludge samples of different origins were studied [5], out of which two samples were selected for laboratory and pilot plant tests, viz., from Ellwangen, a small town in the south of Germany with 25,000 inhabitants, and from an urban settlement in Berlin with 3.5 million inhabitants. The results of the proximate and ultimate analysis are shown in Table 1 [4].

Table 1 Specific fuel parameters of the selected sewage sludge granules

Origin (wastewater treatmen plant)	Composition (free of water) in %							water	volatile	LHV	HHV
	N	C	H	O	S	Cl	ash	in %	in %	[MJ/kg]	[MJ/kg]
Ellwangen	3.33	25.64	3.92	18.01	0.91	n. a.	48.08	6.94	47.07	10.11	11.13
Berlin	3.78	29.02	4.36	17.81	2.87	0.024	44.04	7.41	53.6	11.35	12.42

For the combustion experiments in laboratory scale, dried sludge granules with water content wt < 10% from the selected locations in Germany (Ellwangen and Berlin) were used and then burned in an appropriate combustor. The particles generally had diameters less than 5 mm in size, consisting mostly of granules in the 2~4 mm size range. Both the size and shape of the granules (see figure 2) as well as the need for complete burnout, suggested the use of fluid-bed combustion technology as the appropriate process.

Fig 2. Sewage sludge granules used for the combustion examinations

The thermal drying of the sludge to produce the selected granules was carried out in the wastewater treatment plants by rotary dryer technology. Other suitable drying possibilities are the use of solar radiation by solar dryer technologies or the use of waste heat from other (e.g. metallurgical) processes.

Burnout behavior of sewage sludge granules

Combustion results in the recovery of the combustible matters of the sludge in the form of thermal energy. Fig. 3 illustrates the three main stages involved in the combustion of any carbonaceous fuel in general, or sewage sludge granules in particular:

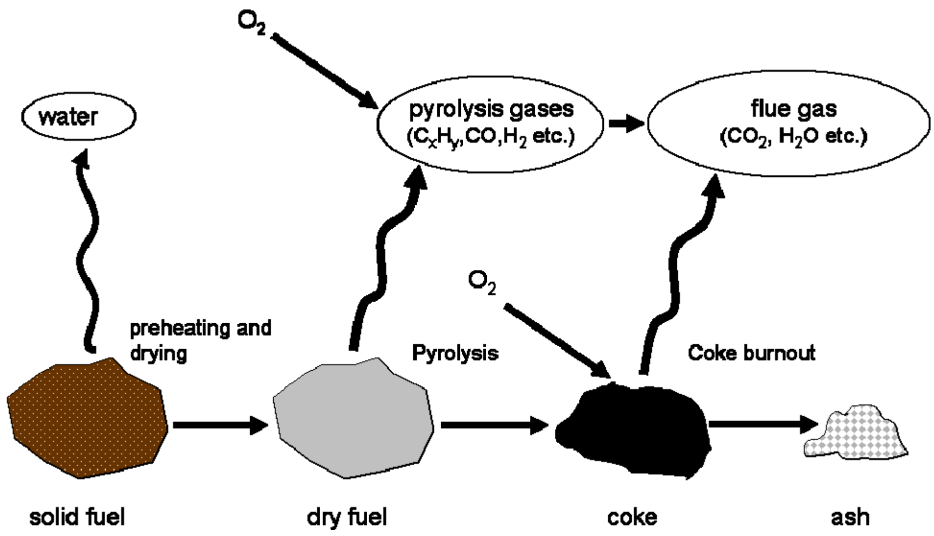

Fig 3. Combustion process for carbonaceous fuel.

The complex reactions, taking place in the three main phases, can be further broken down into individual processes like:

- preheating of fuel particles,
- thermal decomposition of fuel,
- consumption of thermal energy during the decomposition processes,
- diffusion of the gaseous decomposition products (volatile components),
- combustion of volatile components and removal of reaction products,
- diffusion of oxygen from the surrounding to the surface and through the pores of fuel particles to the reaction sites inside the particles,
- combustion of solid residue, coke, and removal of reaction products (CO and CO_2).
- secondary reactions between the carbon in the residue and CO_2.

Based on the results of the sludge analysis, the determination of the burnout behavior of sludge particles was the first step of the technology development activities. Using the laboratory scale test equipment, shown in figure 4, the overall burnout behavior of sludge particles was studied.

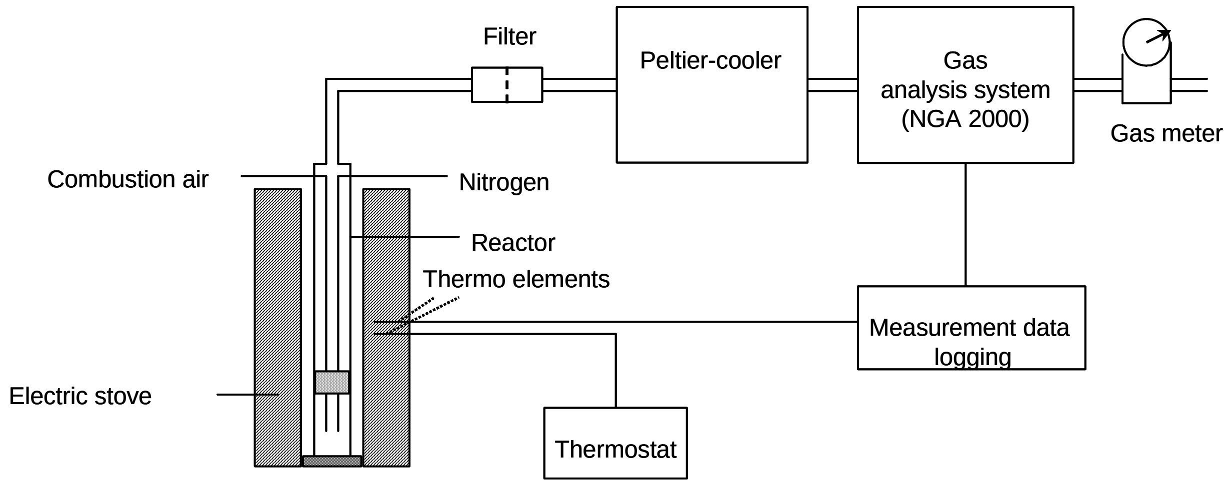

Fig 4. Experimental test plant for determining the burnout behavior of sewage sludge particles.

An enlarged view of the reactor of the test plant is shown in figure 5. In the combustion experiments, approximately 0.1 gram of sewage sludge granules, with diameters of $d_P<1$ mm, $d_P=1\sim2$ mm, $d_P=2\sim3$ mm and $d_P>3$ mm, was used with a volumetric air flow rate of either 30 or 120 l/h. The higher air flow rate corresponds to a linear velocity of 6.1 to 9.2 m/s (depending on the different temperatures used in the experiments) in the reactor, sufficient to fluidize the smaller particles (see table 2).

Table 2 Fluidization velocity of sewage sludge particles in relation to the diameter

Particle diameter in mm	1	2	3	4	5
Fluidization velocity in m/s	4.16	4.95	5.57	6.10	6.58

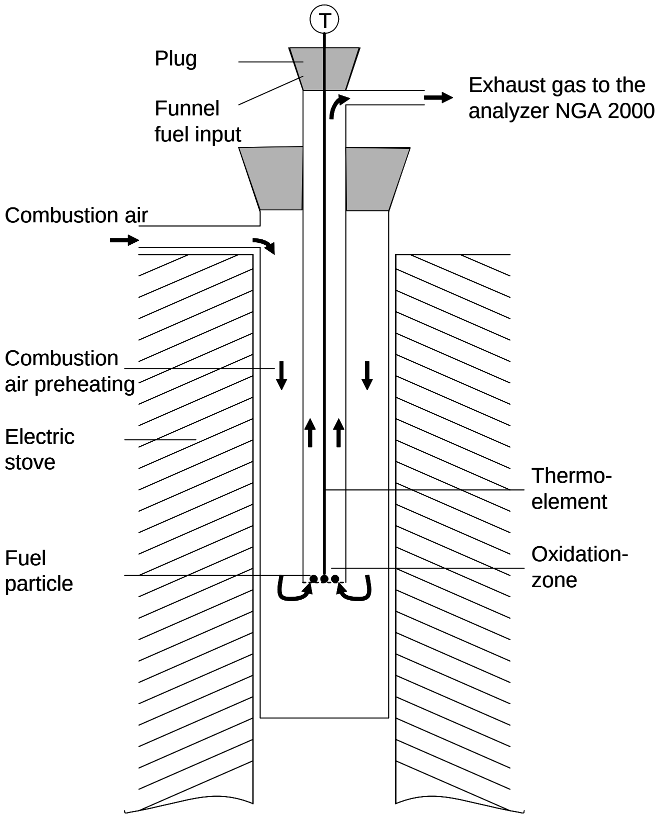

Fig 5. Laboratory reactor for burnout examinations.

Figure 6 shows the overall burnout behavior of single sewage sludge particles determined experimentally by using the test equipment shown in figure 4.

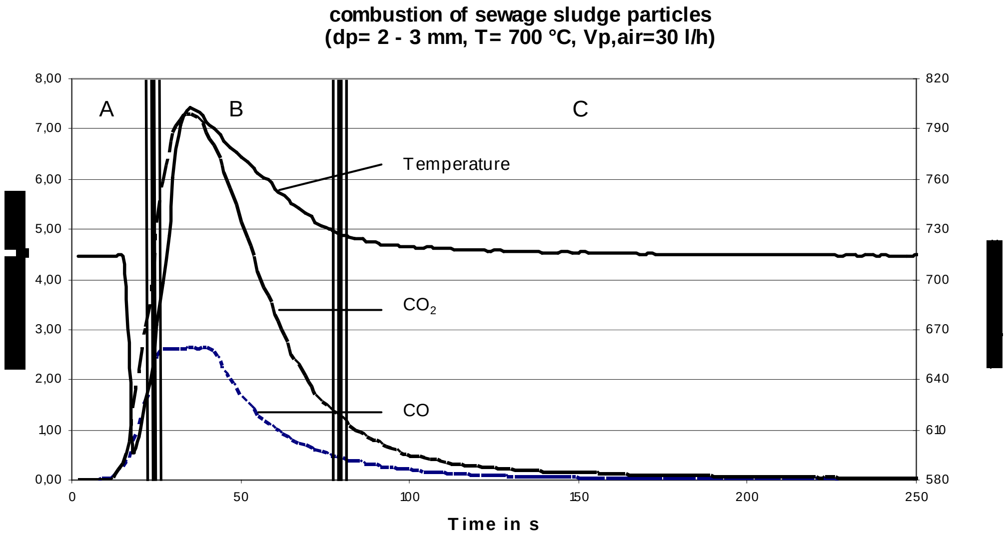

Fig 6. Characteristic single sections of the combustion process of sewage sludge particles, phase A = conditioning time, phase B = burning time of the volatile components, phase C = burnout time of the solid residues (coke) [4].

Table 3 shows the influence of the particle size and the temperature of the reactor on the burnout time of sludge particles for an exemplary air flow rate of 120 l/h.

Table 3 Effect of particle size and temperature on burnout time for air flow rate of 120 l/h

	Burning time in seconds for an air flow rate of 120 l/h		
Particle size	T = 700 °C	T = 900 °C	T = 1050 °C
< 1 mm	25.2	16.8	14.4
1 – 2 mm	40.8	25.2	22.8
2 – 3 mm	55.2	34.8	31.2
> 3 mm	69.6	49.2	40.8

The major particle range of 2~4 mm is completely converted in as little as 70 seconds at a temperature of 700℃. As the burnout time is reduced, the higher the temperature the smaller the fuel particles are, implying that besides temperature the intensity of transport (over the particle surface) is a decisive process parameter. Also the air flow rate and the mixture of the particles with the reaction media are the important process parameters. Figure 7 compares two sets of combustion curves for the 30 and 120 l/h air flow rates, showing how the higher flow rate promoted the transport processes, resulting in faster combustion of the sewage sludge granules.

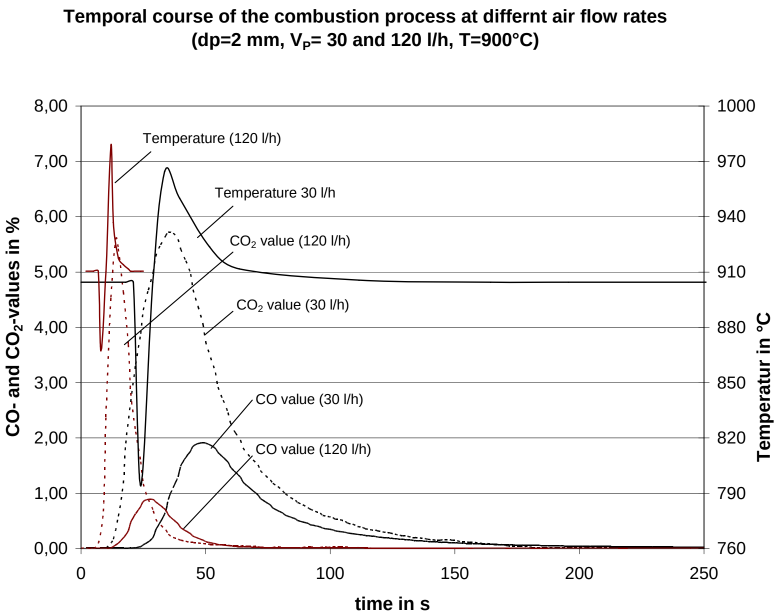

Fig 7. Sewage sludge particles burnout over time at 900℃ and air flow rates of 30 and 120 l/h

Combustion of sewage sludge granules in a small scale (20 kW) pilot plant

To examine combustion of sewage granules in technical systems, a 20 kW small-scale pilot unit inclusive of all ancillary equipment (see figure 8) was designed and tested.

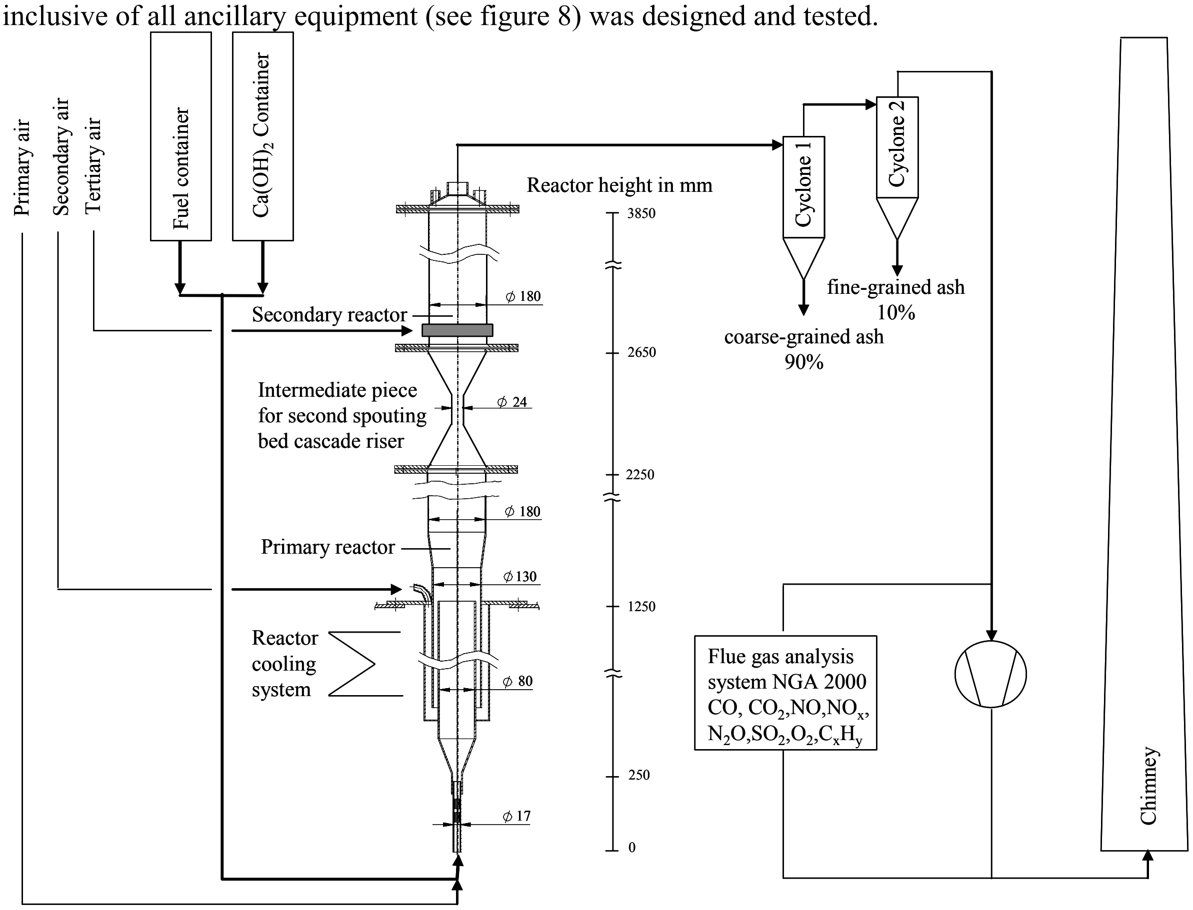

Fig 8. Flow chart of the 20 kW test plant.

Caused by the results of the determination of the fuel characteristics and the overall combustion behavior, the use of fluid-bed technology was suggested as the appropriate combustion process. Problems such as emission and bed agglomeration can be avoided on the basis of a proper design of the technology and a careful selection of suitable operation conditions [6]. The heart of pilot plant was a newly developed fluidized bed reactor, named the “spouted bed cascade system” which was developed as a special feature of the fluidized-bed solution. It is essentially a two-stage conical reactor, 180 mm in diameter (contracted at the lower end to 130 mm), measuring 3850 mm in total height. Fig. 9 illustrates particle movement in the spouting bed reactor. The characteristic feature of combustion in a spouting bed consists of a highly expanded fluidized bed combined with considerable internal circulation of solid feedstock particles. The internal circulation of fuel particles increases conversion, thus making the reactor more efficiency [4]. The combustion air is injected into the sewage particles through an eddy above the bottom inlet of the cone into the primary reactor zone. The velocity of the air flowing through the nozzle should be high enough to create a highly expanded fluidized bed. The particles acquire from the nozzle the necessary kinetic energy for the formation of the fluidized bed. With increasing height, the particles lose their speed and are transported to the wall of the reactor, where a downward particle movement will take place. As the particles move downward, once again they encounter the high-speed airflow from the nozzle and are once more transported upwards. The particles will leave the reactor when their mass is reduced by abrasion and conversion to such an extent that they are pneumatically transported by the upward gas flow.

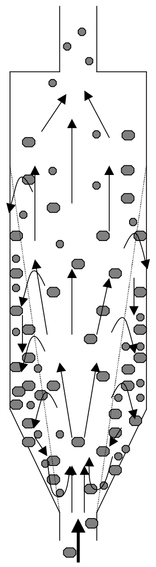

Fig 9. Particle movement in the spouting bed.

The main advantages of the combustion process in a spouted bed system are the excellent mass and heat transport conditions in the reactor. The new system is operated without the addition of any inert bed material and the pressure drop in the reactor is therefore less than that in conventional fluidized bed systems which are operated with such additive inert bed materials. Another advantage of technology is the fact that the pressure drop corresponds only to 2/3 of the weight of bed material (here only fuel and ash, without inert bed material), while in conventional fluidized bed systems the loss of pressure during fluidization corresponds to the weight of the complete bed (fuel + ash + inert bed material). The system was developed as a cascade because the single spouting bed system has limitations on stability conditions. E.g., if the height of the reactor exceeds the maximum altitude of the particles, the air flow would start to revolve around the axis of the conical bottom, and the highly expanded fluidized bed would start to pulsate or even to collapse. This problem also causes limitations of the possible reactor volume of single spouting bed systems and thus also the residence time of particles in the reactor. By using the design of two independent spouting bed reactors in tandem, these problems can be avoided. The use of an intermediate reverse-obverse double-cone piece is the basis for the design of a vertically connected spouting bed cascade, which is more stable in operation than a single spouting bed of the same height. Besides improvement in stability, the cascade principle also causes a reduction in air needed for fluidizing the bed. Beranek et al. [7] indicated that a two-stage cascade system consumed only 78.7% of the air needed for fluidizing a one-stage system having the same height. This is an important precondition for operating the system as a staged combustion process with the result of almost complete burnout of hydrocarbons and carbon monoxide with minimal generation of nitrogen oxides.

Results of the combustion experiments

The combustion sludge granules in the 20 kW test plant was characterized by stationary conditions (balance between fuel entry and ash removal from the rector). As shown in figure 8, the combustion air was added into the reactor in three stages. In order to maintain stable conditions of the fluidized bed in the reactor and to avoid pulsating bed behavior in the lower reactor, it was impossible to create under-stoichiometric conditions (reduction of the primary air flow) in the reduction zone of the primary reactor. Consequently, the fuel-air ratio in the primary reactor was around λ=1. Figure 10 shows the results of combustion experiments with sludge granules from Berlin at a fuel-air ratio of λ=1.06 in the primary reactor, and a total fuel-air ratio of 1.25 inclusive of tertiary air to the secondary reactor.

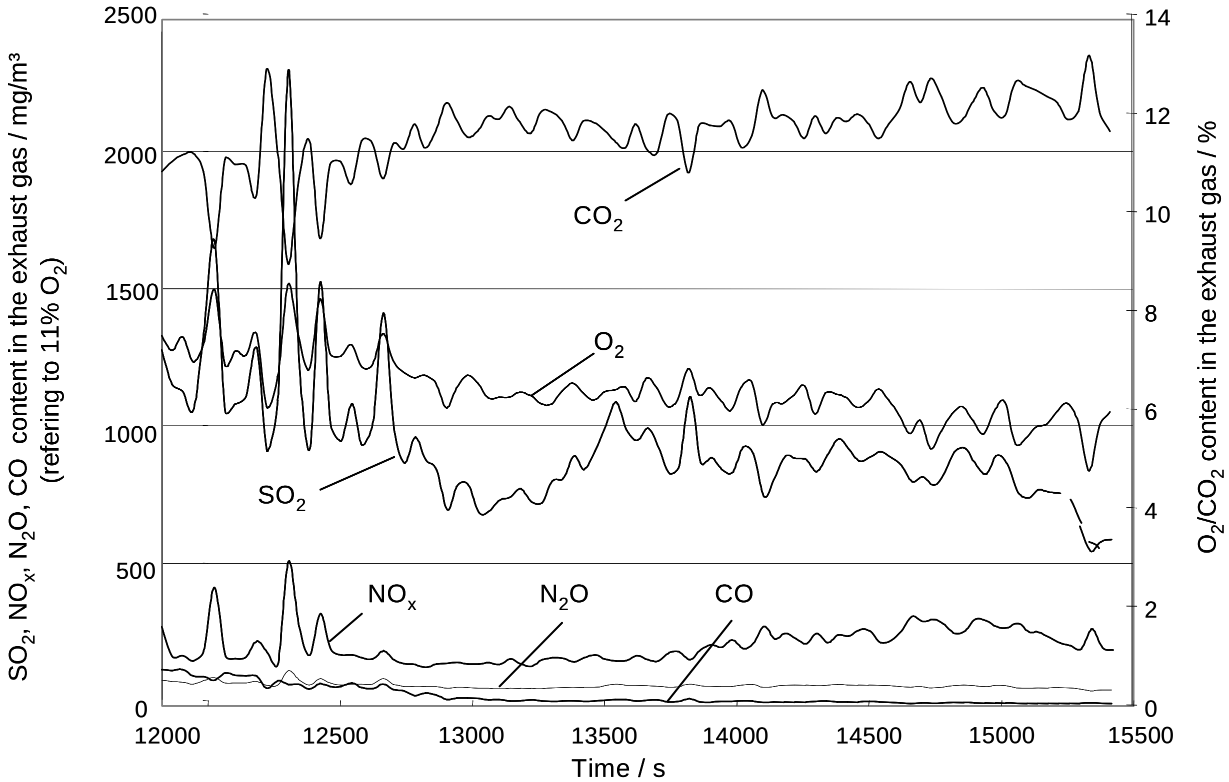

Fig 10. Exhaust gas analysis during the combustion of sewage sludge particles (with 5% from Berlin;20 kW combustion capacity, λ in the primary reactor =1.06, λ total =1.25).

According to the emission limitation regulations in the 17th BImSchV (German Law on Regulation of Garbage Incineration), the results of the measurements shown in figure 10 were converted to a standardized oxygen content of 11% (defined in the 17th BImSchV) in the exhaust gas.

Table 4 Limited values of CO, NO_x and sulfur oxide emissions according to the 17th BImSchV (referring to an oxygen content of 11% respectively)

Flue gas component	CO	NOx (rated as NO_2)	Sulfur oxide
Limited value im mg/m³			
- half hour average value	100	400	200
-daily average value	50	200	50

Organic hydrocarbon concentrations C_xH_y (not shown in figure 10 because of their low values) were 1.5 mg/m³ on average. The measured low CO and C_xH_y values and a very low carbon content in the ash of less than 1% indicate that the fuel utilization is >99%. The greatest difficulties during combustion the sewage sludge collected from Berlin were high sulfur oxide emissions in the exhaust gas. The sulfur oxide emissions are the result of the high sulfur content,nearly 3%, in the sludge as shown in table 1. Because of this high sulfur content $Ca(OH)_2$, 5% of the sludge mass, corresponding to a Ca/S ratio of 0.7/1, was added to the sludge. Usually Ca/S ratio of 2.5/1 to 3/1 (equivalent to some 20% $Ca(OH)_2$) would be used for an effective desulphurization. Such a high $Ca(OH)_2$ addition would lead to other unwanted side effects, e.g. the decrease of the heating value. Because the low amount of 5% $Ca(OH)_2$) is insufficient to reach sulfur oxide values below the daily average value defined in the 17^{th} BImSchV, secondary measures in exhaust gas desulphurization or a reduction of the sulfur content in the sludge of the origin Berlin will be required to fall below the value of 50 mg/m³.

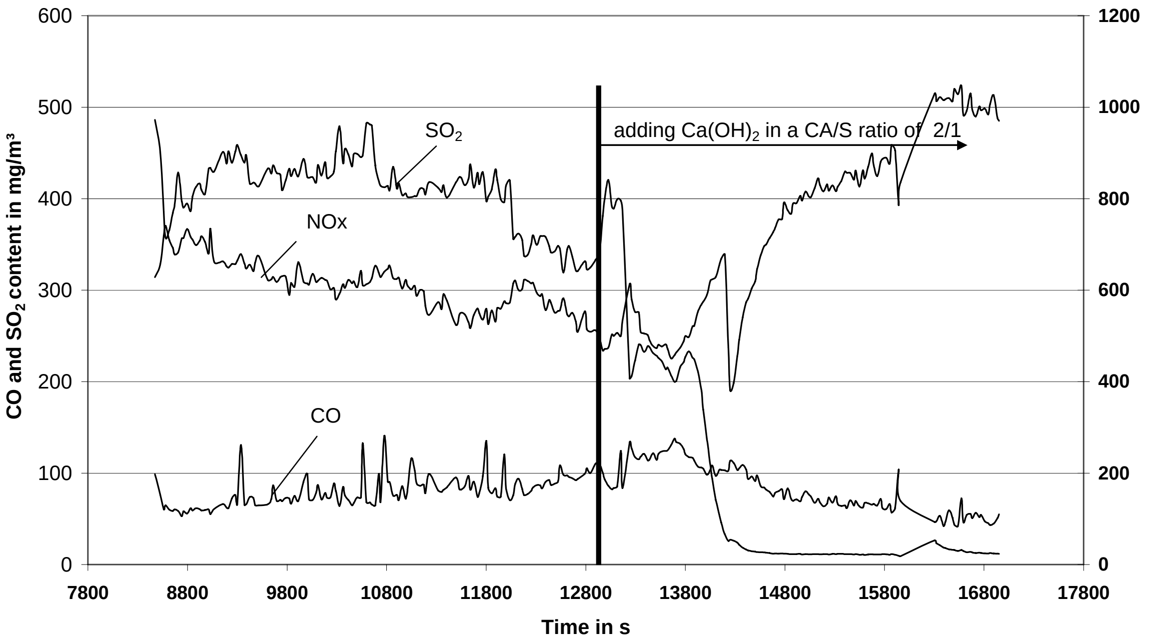

Fig 11. Exhaust gas analysis during the combustion of sewage sludge particles from the origin Ellwangen (18 kW combustion capacity, only primary air supply, λ total =1.25).

Combustion experiments with sludge from the other sewage treatment plant of the origin Ellwangen demonstrated that keeping within the limits of the 17th BImSchV is easily possible if the sulfur content is lower than 1%. The combustion test with the sludge from Ellwangen shown in Fig. 11 were carried out up to 13,000 seconds without adding any Ca(OH)2, and after this time, with a $Ca(OH)_2$ content of 5% (corresponding to a Ca/S ratio of 2/1). The results, already converted to an oxygen content of 11% show that the CO values lie in a similar range to those in Figure 10. Keeping within the limit should, therefore, be possible. The data also show that in order to keep within the limit for sulfur oxide emissions, the addition of a sulfur-absorbing medium is required. The sulfur oxide reduction of about 97.5% can be considered as adequate. The data as presented in Figure 11 also show an increase in nitric oxide emissions as a consequence of sulfur oxide reduction.

Conclusion

Experimental results show that the spouted bed cascade system is highly suitable for combustion of dried sewage sludge particles. The reactor has a simple design which will substantially reduce investment costs for commercial plants. Secondary facilities required for conventional CFB systems for fuel recirculation are not necessary for this process. With this reactor system, more or less complete fuel utilization could be achieved. As a result of optimization measures, substantial emission reductions of harmful substances, as limited in the 17th BImSchV, could be reached. It was also shown that only limited amounts of CO and C_xH_y are present in the flue gas. Neither any chlorine nor fluorine was found in the flue gas. It was further shown that by addition of a sufficiently large amount of $Ca(OH)_2$, emission of sulfur oxide could be largely reduced. Limits as set by the German Law on Regulation of Garbage Incineration could be adhered to with the combustion of the sewage sludge from the treatment plant in Ellwangen by adding $Ca(OH)_2$ at a Ca/S ratio of 2/1. For combustion of sewage sludge with high sulfur contents, however, alternative measures will be necessary. Throughout the present experiment, it was not possible to keep within the limit for nitric oxide, as it was not possible to create under-stoichiometric conditions for air in the primary reactor zone. In order to achieve this, further modifications of the reactor geometry will be necessary. With view to the results so far achieved, further experiments in this area seem promising.

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