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SMALL SCALE INCINERATOR FOR BIOMASS, WITH A BUBBLING FLUIDIZED BED. I. COMBUSTION OF SEWAGE SLUDGE

Results are presented, obtained when sewage sludge was burned in a purpose-designed industrial installation, comprising a 1.5 MW bubbling fluidised bed combustor. Dried sewage sludge was used in the tests. The combustion process was stable, and since the moisture content of the dried sludge was low, no auxiliary fuel was required. Analysis of the flue gases has shown that the concentrations of SO_2 and NO_x are somewhat elevated, on account of rather high combined S and N content in the sludge. The results have confirmed that the technological solutions used were correct and that they can be used for economically effective and ecologically safe local disposal of wastes by thermal utilisation.

INTRODUCTION

The development and spread of technical civilisation can bring about progressive degradation of surface and ground waters. New and/or better methods of disposing of liquid wastes are thus required. The introduction of modern methods of waste water treatment (in Poland, particularly over 1991-2002, when many sewage treatment plants were modernised and new ones built), brought about a large increase in the volume of water treated and the quantity of sewage sludge produced. It is usually accepted that treated water can be used in agriculture or discharged to streams and rivers. However, ecologically safe disposal of the sewage sludge largely remains an unsolved problem. The methods used to deal with the sewage sludge produced in Poland in the year 2000 are listed in Table 1. The first place is taken by direct use of the sludge in land re-cultivation and as a fertiliser. This practice, however, has some disadvantages. Because of the possibility of contamination with toxic or harmful substances, the sludge may not meet the rigorous requirements necessary for a fertiliser. Many norms, particularly those concerning the content of heavy metals, such as zinc and cadmium, are exceeded. Removing such contaminants would be both difficult and costly. Also, because of very considerable variability in the chemical composition of the sludge, every batch to be used on cultivated land ought to be analysed, which adds to overall costs.

Tab. 1. The structure of the utilisation/disposal of sewage in Poland in the year 2000. Quantities in terms of dry mass.

Production, use and disposal	Local waste water treatment plants		Industrial water treatment plants		Total	
	mass, 10^3 tons	%	mass, 10^3 tons	%	mass, 10^3 tons	%
Production	359.8	100.0	703.3	100.0	1063.1	100.0
Use/disposal						
Industry	28.3	7.9	126.6	18.0	154.9	14.6
Agriculture	50.6	14.1	161.6	23.0	212.2	20.0
Composting	25.5	7.1	2.5	0.4	28.0	2.6
Incineration	5.9	1.6	28.2	4.0	34.1	3.2
Deposition	151.6	42.1	322.9	45.9	474.5	44.6
Other	97.9	27.2	61.5	8.7	159.4	15.0

Since 1980 the total volume of waste waters produced has been gradually falling [1]. This is a result of more careful management of water use both in industry and in homes. At the same time, the quantity of sludge obtained per unit volume of waste water has been increasing. According to Bernacka and Pawłowska [2], over 1997-2001 the sludge produced has increased from 0.204 do 0.251 kg dry mass/m^3 of treated waste water. The increase is also partly due to more effective waste water purification and changes in the type and quantity of the flocculants employed.

Sewage sludge consists of solid particles dispersed in water and contains a variety of materials, ranging from mineral matter, via various organic substances, down to e.g. biologically active eggs of parasites. If it is kept without further treatment, decay processes begin and an objectionable odour is produced. The exact properties of the sludge produced by a given waste water treatment plant, such as the solids content and the composition of the solids, the pH value etc. depend on the purification method used. Table 2 present examples of the composition of raw Polish sewage sludge from several sources.

Tab. 2. Selected chemical elements present in raw sewage sludge [3, 4]. Concentrations with respect to dry matter

	Major constituents, [g/kg, dry mass]						Minor constituents, [mg/kg, dry mass]				
Dry mass	N	P	Ca	S	K	Mg	Cd	Cr	Cu	Ni	Pb
13 – 33	9 - 86	1 - 40	10-550	1 - 8	1 - 6	5 - 420	0.9 - 61	10-1030	43 - 230	1.5 - 25	5 - 420

Dry sewage sludge usually contains 25 to 75 % organic matter. The content of the biologically important elements is elevated. Sulphur and nitrogen can come from e.g. human and animal hair, nails and skin and phosphorus from detergents. The concentrations of toxic substances and heavy metals [5] depend on the sources of the original wastewaters (domestic or industrial) and the sewage system employed (e.g. if the system takes in runoff, most pollutants are diluted). Because the sludge is high in organic matter, dry sludge can behave as a fuel. The fuel value depends on the type of sludge and the proportion of organic matter. For a sludge with about 30% of incombustible inorganic matter, the fuel value is about 14 [MJ/kg]. For fermented sludge, after a proportion of combustibles has been lost in the gas produced, the fuel value is lower by about 2 [MJ/kg] [6].

Since wastes should be utilised close to their source, thermal treatment by incineration or pyrolysis is a rational solution. However, such methods are still uncommon in Poland, although there have been attempts to burn sewage sludge together with municipal solid wastes or with coal, in power stations or cement kilns.

EXPERIMENTAL INSTALLATION

A scheme representing the proposed bubbling fluidised bed technology for the utilisation of sewage sludge is given in Fig. 1. This comprehensive solution provides for full sanitation and utilisation of the sludge in a single installation, practically at the source. Such installations could operate at small and medium waste water treatment plants, serving regions with 20 to 80 thousand inhabitants.

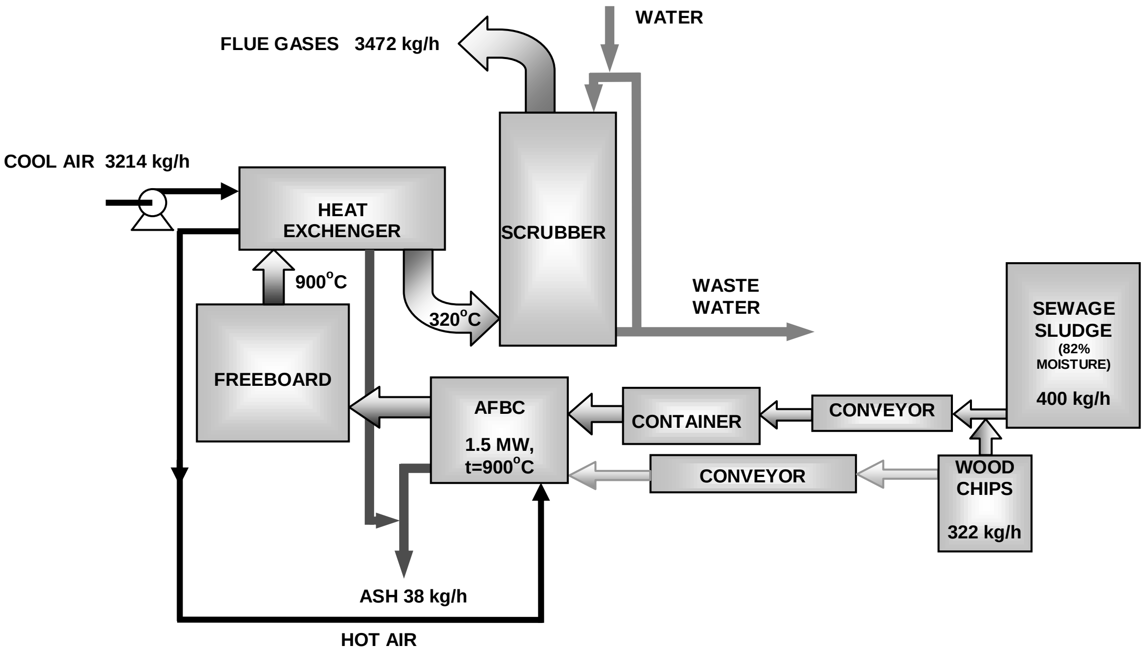

Fig. 1. A scheme of the proposed technology for the incineration of wet sewage sludge

The installation has been designed for the thermal treatment of about 400 kg/h of raw sewage sludge, containing about 18% of solids. A low proportion of combustibles in the wet sludge and thus low heat of combustion makes it necessary to use a supplementary fuel (wood chips). Calculations have shown that to achieve the required throughput of raw sewage sludge, it is necessary to burn about 320 kg/h of wood chips, with 30% moisture content. The air required for the co-combustion process is 2500 Nm^3/h. The process would give about 3000 Nm^3/h of flue gases and 38 kg/h of ash. To improve the thermal efficiency of the installation, it is important that the fluidising air should be preheated to at least 400 ^oC. This is achieved in the heat recuperator, with the flue gases as the source of heat. At the exhaust end of the installation, the flue gases are passed through a scrubber system. Its chief functions are to bring down the concentration of SO_2 (there is no desulphurisation in the bed) and to capture any particulates escaping the dust removal system.

An installation for the thermal utilisation of sewage sludge, embodying the above considerations has been designed within the project "Sludge for Heat", financed by the UE and Polish Ministry of Science and Information Society Technologies. The installation has been constructed, assembled and put through tests at Niepołomice near Kraków. It is intended for the combustion or co-combustion of sewage sludge with wood chips or segregated municipal solid waste.

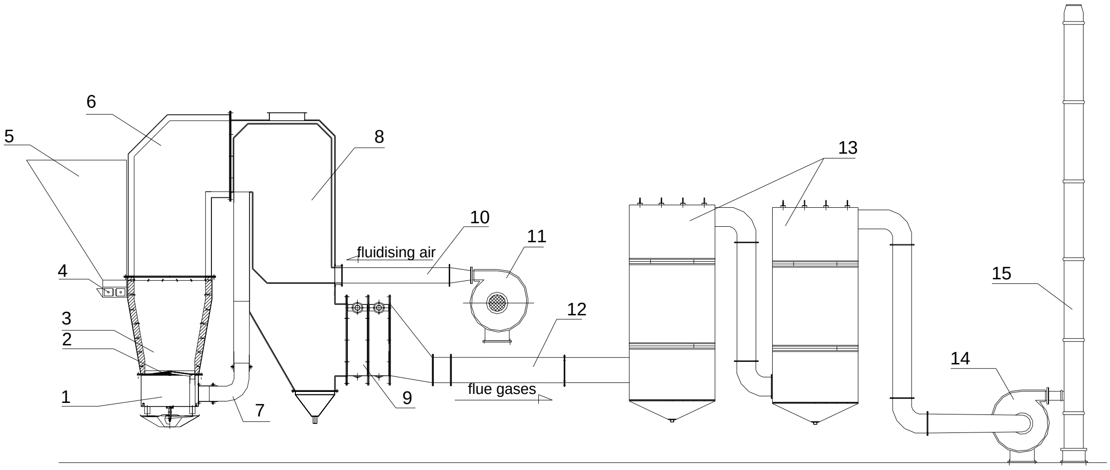

Fig. 2. A scheme of the installation for burning sewage sludge built
at the Waste Water Treatment Plant at Niepołomice

The most important element of the installation is the 1.5 MW bubbling fluidised bed combustor, Fig.2. The combustor unit comprises a wind box (1), with a distributor (2) 0.5 m^2 in area affixed at the top, a combustion chamber (3) and freeboard space (6), where the combustion process should go to completion. The sewage sludge and auxiliary fuel (wood chips), are supplied by a screw feeder and a conveyor belt respectively, to two bunkers (5). From the bunkers, using pipe feeders (4) and via sloping ducts the fuels are directed to the combustion chamber (3). Hot flue gases leaving the freeboard are directed to a countercurrent gas-gas heat exchanger - recuperator (8). Its function is to preheat the fluidising air to a suitable temperature. Hot air from the recuperator (8), via a wind channel (7), reaches the wind box (1) and passing through the distributor (2) enters the combustion chamber (3). In addition, the system contains tubular heat exchangers (9), to provide hot water. The construction of the wind channel (7) is such as to facilitate installing tubular heat exchangers, depending on need, either between the combustor and the panel heat exchanger (8) or beyond the recuperator (8). The air flow rate is measured in the duct (10) between the air pressure fan (11) and the recuperator (8). The duct is equipped with a flap seal which can be used for cutting off the air supply to the combustor instantaneously. After leaving the heat exchangers the flue gases travel along a flue duct (12) to a scrubber system (13), from where an exhaust fan (14) draws them into the chimney (15). In the flue and air ducts, freeboard and recuperator sockets are provided where sensors can be placed to measure the temperature and through which probes can be inserted to withdraw gases for chemical analysis.

The whole installation has been designed on the modular principle. Individual elements, such as the combustor, heat recuperator, scrubbers, tubular heat exchangers etc. can be placed inside containers for transport to the site where the installation is to operate. In addition, the construction of the elements is designated in such a manner that makes it possible to assemble them in different configurations, depending on the needs or requirements. The materials used to fabricate the parts were chrome-nickel steel 1H18N9T and carbon construction steel St3S. Internal insulation of the combustor is made of hard ceramic and the combustion chamber is partly lined with ceramic fibre insulating mats. On the outside, the combustor and the panel heat exchanger are insulated thermally with mineral wool, interlaid with aluminium foil.

To maintain correct operating conditions, the fluidised bed reactor is provided with monitoring and automatic control systems. Because of the manner in which the installation is controlled, the most important operational parameters are the fluidised bed temperature, the fluidising air stream and the pressure difference across the bed.

The temperature of the bed can be subject to considerable changes and hence the temperature control system depends on a regulating device operating with a proportional algorithm and with a fixed working point. Such an algorithm requires that the regulator must be re-tuned if the properties of the fuel change drastically and under steady conditions leads to non-zero error of regulation. One of its advantages is insensitivity to brief impulse interferences, which facilitates the analysis of the reactions of the system being controlled.

The optimum fluidisation velocity is selected experimentally and is maintained with the aid of a regulator with a proportional-integral algorithm. The pressure fan is operated with continuous control of the air stream. The air flow rate through the reactor must always lie between that for minimum fluidisation and for pneumatic transport of the bed material.

The pressure drop across the bed provides a signal to control the removal of solids from the bed. The signal can also indicate that the bed height is falling through excessive elutriation of the bed material or for any other reason.

The control system used in the installation is based on a programmable logic controller *(PLC)*, type SAIA - BURGESS PCD2.M150. The controller is connected to a control panel ESA VT505. This is used to introduce the settings required and can provide simple visualisation of the state of the installation, showing the values of the process parameters (both numerically and graphically). The controller is also connected to an industrial computer, provided for advanced steering of the whole installation. In this system the Axeda Supervisor program has been used for the visualisation of the parameters of the process (numerical values, with indications of trends), registering data on the computer disc, visualisation of the state of the various mechanisms (ventilator fans, pumps, fuel feed) and detection and registration of incorrect operation. The automatic system can be overridden by switching over to manual steering.

TEST PROCEDURE, RESULTS AND DISCUSSION

During the operation of the combustor, the temperatures of the bed, of the flue gases entering and leaving the recuperator and of the gases at the exit from the scrubber were monitored continuously. The temperature was measured using Ni-NiCr thermocouples placed in the bed, at the top of the freeboard and beyond the scrubber system. The flue gases were analysed before and after the scrubber, also on a continuous basis. The results after the scrubber came from a MRU VarioPlus^{TM} instrument. The concentrations of O_2, NO, NO_2 and CO were determined using electrochemical sensors, to the nearest 0.1 % for O_2 and 1 ppm (vol.) for the others. For the concentrations of CO_2 and of organics IR absorption was used and the measurements were to the nearest 0.1 % and 1 ppm respectively. The relative error in the O_2 and CO concentrations did not exceed 1%, and for the other concentrations, 5%. The concentrations of polyaromatic hydrocarbons (PAH) in an aqueous extract of the sewage sludge, samples of water from the scrubber and water condensed from the chimney, ash from the ash trap and flue dust collected from the chimney duct were determined chromatographically. Samples of flue dust and of the condensate were collected in accordance with the requirements of EN 1948. Organic substances were extracted from the flue dust using dichloromethane. Water from the scrubber and the condensate were initially purified in extraction columns SPE Discovery® DSC-18 (Supelco), with final extraction with dichloromethane. The extracts were analysed chromatographically, using a GC/MS Clarus 500 (Perkin Elmer) instrument, with a capillary column, type DB-5 (30 m×0.25 mm×0.25 μm). During the current phase of the project it has only been possible to carry out tests using previously accumulated sewage sludge. Because of the conditions under which it had been stored, its moisture content was 7%. In the tests described here the installation was operated under three sets of conditions. First (Fig. 3, time 0 – 1300 s) the working parameters of the feed system were selected experimentally. Second (Fig. 3, time 1300 – 2700 s), the installation was run under "typical" conditions. In the second phase of this period (from about 2300 s) the fluidising air stream was gradually reduced, which amounted to lowering the thermal power. Third (Fig. 3, after about 2700 s), the working parameters of the installation were registered to assess the effect of automatic control of the combustion process with disturbances in the sewage sludge feed. The operation of the sewage sludge feed (and auxiliary fuel feed, if used) is very important in determining the quality of combustion in the bubbling fluidised bed. In the installation tested, this is not continuous but intermittent. If the operator attempts to override the automatic controller by switching to manual control, this may lead to perturbations in the process. Such perturbations can also be due to incorrect choice of the amount of sewage sludge added in a single feed system cycle. Figure 3 (period between 0 – 1300 s) shows the bed temperature and concentrations of selected flue gas components during sewage sludge combustion. On adding too large a batch of the sludge the automatic system reacted by cutting off the fuel supply. This led to a sudden increase in the concentration of O_2 and a drop in that of CO_2. Interruption of the fuel supply was consistent with the observed changes in the concentrations of SO_2 and NO, derived practically only from the S and N from the sludge. The drop in these concentrations was very marked, with SO_2 down from about 270 to 130 ppm and NO

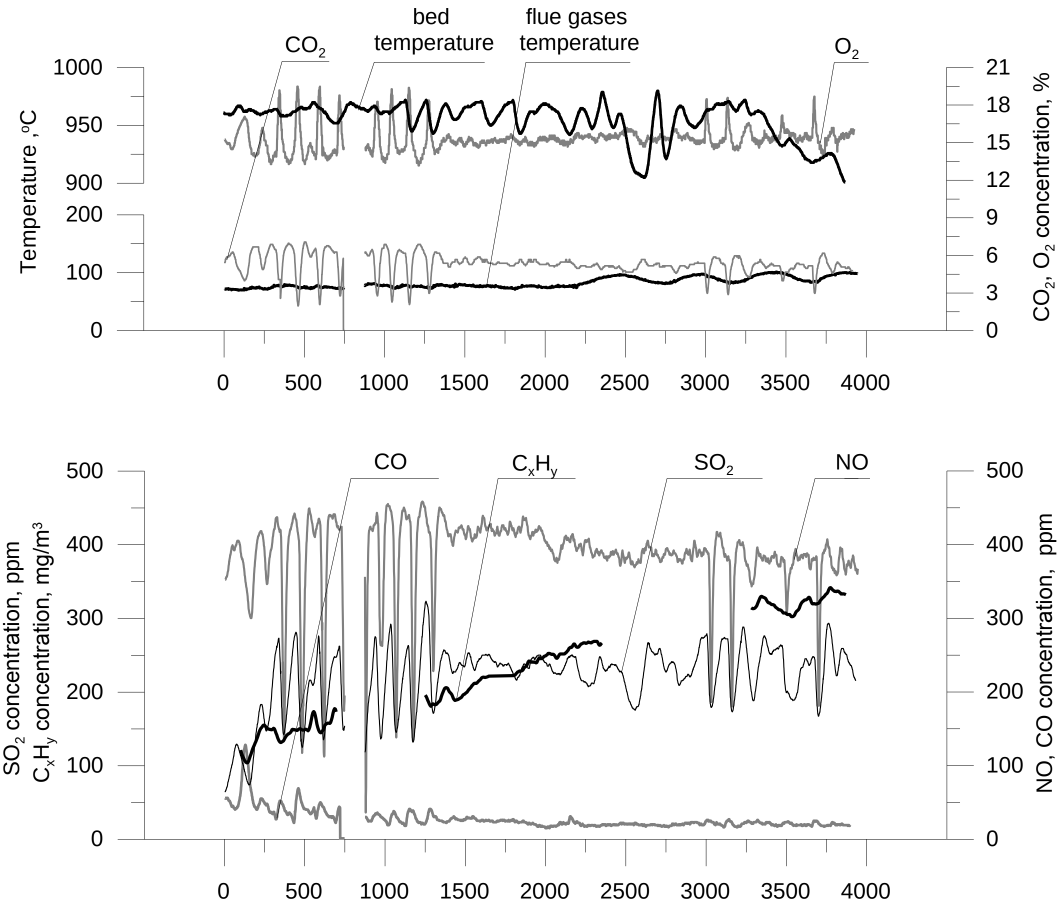

Fig. 3. Temperature records and flue gas concentrations observed when sewage sludge was burned in the 1.5 MW fluidised bed combustor

from 440 to 120 ppm. The burn-out of the char is reflected as a slight rise in the CO concentration. These results point to the importance of the fuel feed system and the ease with which an inappropriate choice of the quantity of sewage sludge fed in per cycle can affect the process. At the same time, in spite of disturbance in the feed system and the flue gas composition being strongly affected, the process remains thermally stable. When the regulation settings were changed, to reduce the duration of a cycle of the feed system, the operation of the installation became smoother.

A situation that an operator of a sewage incineration plant can typically encounter is the need to reduce the quantity of sludge burned. In order to maintain the combustor temperature at the correct level, it is necessary to reduce the fluidising air stream. For a bubbling fluidised bed this brings about a number of effects. Such a situation was simulated during the second stage of the tests and the results are shown in Fig. 3, at times 1300 - 2700 s. The concentrations of O_2 and CO_2 were steady and the process was stable, with the control system maintaining the bed temperature at 960±10 °C. The SO_2 and NO concentrations oscillated around a steady level. Only the concentration of organic components, VOC, showed a tendency to increase with time, from the beginning of the run. This could result from a gradual rise in the temperature of the water circulating in the scrubber and thus the efficiency of the absorption falling off with time. When the fluidising air stream was reduced by about 20% (at 2300 s), after about 2 min. the bed temperature started to fall. The control system automatically adjusted the fuel feed and the temperature rose again. Since the correction had been overdone, the temperature rose too far and the system again cut off the fuel. This occurred a number of times. As in the first part of the test, changes in the fuel feed particularly strongly affected the concentrations of O_2, CO_2, NO i SO_2 (e.g. at 3000, 3140 and 3680 s). The test was terminated with the bed temperature at 890 ^oC, although the composition of the flue gases and, in particular, the concentrations of CO, NO and SO_2, were not too different from those observed at full load and with the bed hotter by about 50 ^oC.

CONCLUSIONS

1. Thermal utilisation of damp sewage sludge, without using an appreciable proportion of conventional fuels is possible.
2. The combustion process can be steady and can be automatically controlled.
3. In the tests carried out the average CO concentration (at 11% O_2) was 45.1 ± 9.6 mg/m^3, showing that the combustion process was highly effective.
4. Sewage sludge is a waste which can be high in chemically combined S and N. In the flue gases the concentrations (at 11% O_2) of NO_x (as NO_2) and SO_2 were, respectively: 1438 ± 219 mg/m^3 and 1184 ± 241 mg/m^3.

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