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Fluidized Bed Incineration of Sewage Sludge: A Strategy for the Design of the Incinerator and the Future for Incinerator Ash Utilization

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In 1991, the sewage sludge production from municipal sewage treatment plants in Flanders was about 45000 ton/year in terms of dry solids.
With additional sewage treatment plants being built, the sludge quantity will dramatically increase. Per capita and per day, about 50 grams of dry solids will be produced, to reach a total production in excess of 100000 ton/year by the end of the century.
Most of the sludge is currently disposed by landfill, but it has become more and more difficult to find suitable sites for landfill, particularly in and around large cities.
Reduction of the sludge volume to be disposed, therefore, is often a matter of primary concern. Of the new processes developed to ensure the safe disposal of sludges from municipal and industrial effluent treatment plants, the fluidized bed incinerator is attracting increasing interest.
This paper presents a practical strategy for their design and concentrates on the eventual utilization and beneficiation of incinerator ash, which can reduce the total cost of sludge treatment and disposal.

1 Introduction

Sludge from industrial water treatment and from municipal sewage is ultimately disposed in four ways:

- tipping on land
- disposal at sea
- spreading on agricultural land (in the case of sewage sludge)
- incineration

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Increasingly there are restrictions on disposal on land or at sea because of pollution problems, and there is therefore increasing interest in the incineration of sludge alone or together with refuse to yield a hygienic ash of relatively small volume which can be more readily disposed [1] or eventually utilized [2].

Since most of the treatment plants handle mixed domestic and industrial influents, the sludge composition therefore contains the traditional elements i.e. organic matter, nitrogen, phosphorus, potassium, calcium and magnesium, but also high concentrations of heavy metals i.e. Zn, Cu, Pb, Cr, Ni, Cd, Hg. Table 1 summarizes average compositions for sewage sludge in Flanders (1989)

Table 1.
Average sludge composition (on dry solids basis)

organic matter	%	49.6
Kjeldahl nitrogen	%	3.1
P_2O_5	%	4.4
K_2O	%	0.39
CaO	%	15.0
MgO	%	0.6
Fe	%	3.49
Na	ppm	3839
Zn	ppm	2730
Cu	ppm	766
Cr	ppm	360
Pb	ppm	204
Ni	ppm	136
Cd	ppm	12.5
Hg	ppm	2.1

The legislation for agricultural use of sludge is in full evolution and standards for acceptable concentrations of sludge for agricultural application become more severe. Table 2 illustrates current standards.

Table 2.
Acceptable concentrations for agricultural application of sewage sludge

mg/kg DS	EC	Holland >1.1.93	Flanders >1.12.92	Holland >1.5.95
Zn	2500-4000	2000	2500	300
Cu	1000-1750	600	750	75
Pb	750-1200	500	600	225
Cr	1000-1750	500	500	75
Ni	300-400	100	100	38
Cd	20-40	10	12	1.25
Hg	16-25	10	10	0.75
As	-	-	-	25

Evidently, some current sewage concentrations already exceed the standards. With reducing levels, virtually no sewage sludge will be used on land.

2 Incineration of sludges

Incineration has the highest potential as treatment method. It fully destroys organic matter and produces an organic ash of high alkali content.

Due to the presence of the alkali, this ash can be used in landfills (reduced leaching due to insoluble metaloxides in alkaline conditions). In view of increasing costs for landfill disposal, currently between 150 and 300 US\$/ton, new ways of utilization of the ash need to be investigated. Some suggestions will be summarized further in the paper.

Incineration furnaces may be single or multiple hearth furnaces, or fluidized bed combustors. The latter are particularly suitable for sludges which have too low a combustible content (high water, high ash content) to be burned in conventional furnaces.

Although a large number of fluidized beds are now in operation, little has been published and this paper is an attempt to provide a basis for the design, and summarizes initial procedures of Baeyens et al. [3].

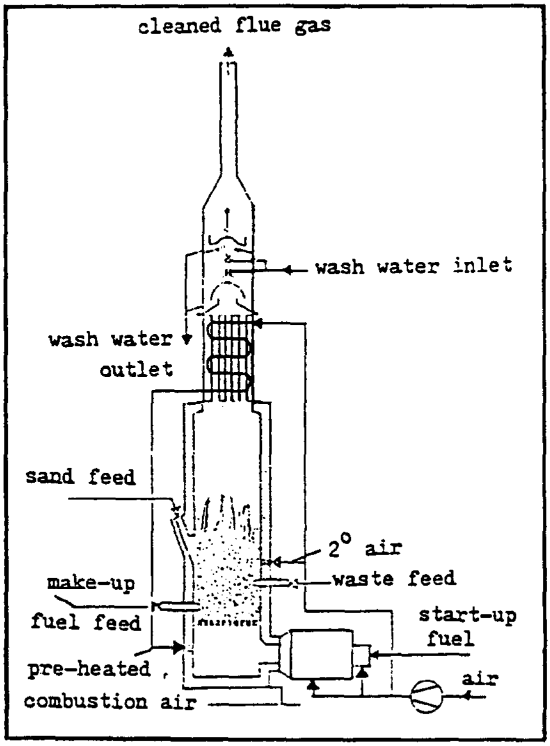

Figure 1. Sludge incineration with heat recovery - Lurgi Patent

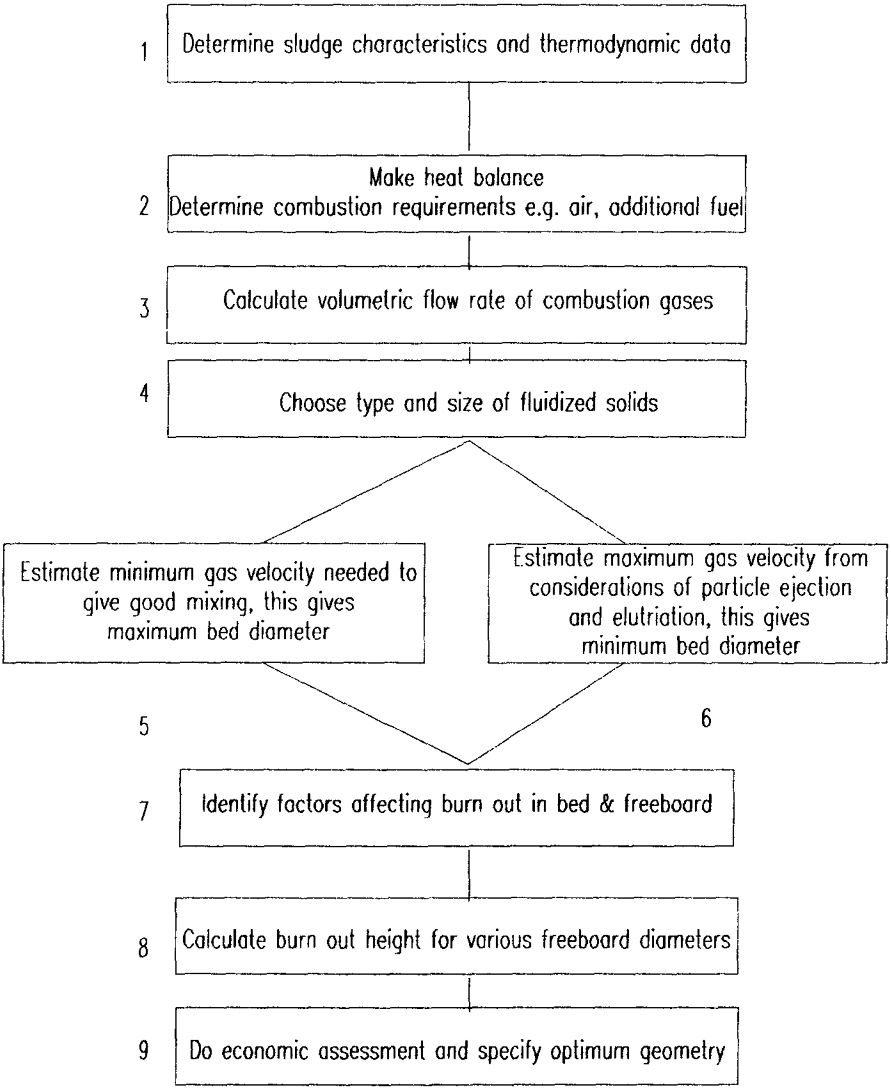

Figure 2. Flow diagram for the design of a fluid bed incinerator

3 Design procedure

3.1 General comments

Figure 1, published by courtesy of Lurgi Apparate-Technik GmbH, illustrates a typical fluid bed incinerator. A bed of inert material, usually coarse sand, is fluidized at high velocity in a refractory shell which may be cylindrical or slightly tapered. Primary combustion air provides the gas for fluidization and secondary air is admitted above the bed. Depending on the nature and composition of the sludge, the feed may be introduced by pumps or screw feeders into and/or above the fluidized bed. Evaporation of water and partial combustion being completed in the freeboard. After energy recovery, the flue gases are further cooled and cleaned to meet local air pollution control requirements.

The efficiency of the incinerator depends both on geometrical and operational factors such as fuel and sludge distribution, bed material, bed height and diameter, mixing, combustion rates, operating temperature, elutriation, etc. These will be considered during the stages of the design procedure as outlined in Figure 2. Similar procedures have been presented for gas/solid reactions by Baeyens et al. [4], [5].

3.2 Design logics

Each of the design stages in Figure 2 is numbered and the numbers correspond to the explanatory notes in the text. Wherever possible we have tried to verify the basic design criteria by comparison with large scale data made available to us.

Note 1

The sludge characteristics (% H_2O, ash, composition of combustibles) and thermodynamic data are generally available or can be estimated with sufficient accuracy.

Sludges vary considerably both in concentration (5-20 % solids for refinery sludges [6], 15-40 % for dewatered sewage sludges [1]), and the percent combustibles (50-75 % of dry solids) and consequently their caloric values vary. Depending on the composition of combustibles, the desired operating temperature and the amount of heat recovery made that the minimum solids concentration required for autothermal operation varies. This is illustrated in Figure 3 for typical commercial applications.

Even for complex systems such as municipal sludges the composition of the organic matter averages to $(CH_{1.65}O_{0.34}N_{0.1})_m$. Depending on the ash content the caloric value lies between 800 and 5500 kcal/kg dry solids containing 20 % to 100 % combustibles. The calorific value of digested sludges is 10-15 % lower.

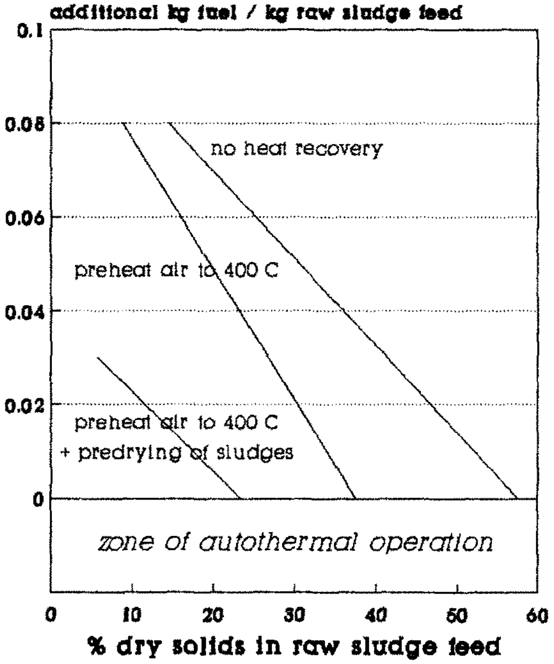

Figure 3. Fuel required for combustion of sewage sludge with CV of 2000 kcal/kg dry solids, combustible concn 50 % of dry solids, temp=800°C, excess air 20%, fuel 9000 kcal/kg

Note 2

The stoichiometry enables us to calculate the air requirements for complete combustion allowing for approximately 20 % excess air. In general 80 % of the total air is introduced through the windbox and 20 % into the freeboard. Bed temperatures are generally 700-900 °C (see Note 4). Air preheating and preconditioning/preheating of the sludges are commonly used, but sludge drying gives rise to the evaporation of malodorous components. These require further degradation by combustion in the fluid bed, and since this constitutes an additional thermal load it is desirable to keep the volume of associated air as small as possible by using indirectly heated sludge dryers.. Sludge handling properties are different at various concentrations. The lower limit for readily pumpable sewage sludge is approximately 92 % water [7]. Sludges of any sort with less than 82 % water generally have to be fed by screw conveyor or slinger.

Note 3

The volumetric flow rate of gases, including water vapor, into the windbox, through the bed, and into the freeboard can now be calculated. Special burners are often used at start up to increase the volumetric flow rate of gas because the fan is often not large enough to fluidize the bed with cold air.

Note 4

Generally the inert solids are quartz sand in the size range of 0.6-3 mm. Coarse particles are used not only because they have higher terminal and incipient fluidization velocities but also because they are less affected by stickiness due to fewer interparticle contacts and greater particle momentum which breaks incipient bonds.

Special problems occur [6] when treating chemical sludges or whenever salt concentrations are high. The possible formation of eutectic mixtures with a melting point close to the bed operating temperature (e.g. 800 °C for $Na_2O.3SiO_2$) can cause defluidization and necessitates a decrease in operating temperature, the use of coarse solids other than silica sand or the addition of clay or special metal oxides in the feed so as to bind the alkali silicates to compounds with higher melting points.

Note 5

The high heat and mass transfer rates required in a fluidized bed combustor are associated with rapid solids mixing and are only achieved within a gas velocity range U_{min} - U_{max}. Our earlier mixing and heat transfer studies [8], [9] on powders ranging from 40 to 1850 μm, together with published data enabled us to establish the range of gas velocities for optimum hydrodynamics and heat transfer [10].

Within the particle size range of 0.8 to 2.2 mm, the following optimum ratios apply:

$$\frac{U_{min}}{U_0} \approx 1.5 + 0.5\left(\frac{2.2 - \bar{d}_{sv}}{2.2}\right) \tag{1}$$

$$\frac{U_{max}}{U_0} \approx 3.0 + \left(\frac{2.2 - \bar{d}_{sv}}{2.2}\right) \tag{2}$$

$\bar{d}_{sv}$ is in mm.

Most of the beds operate well above U_{min} in order to reduce the bed diameter (see Note 6).

The minimum fluidization velocities at elevated temperatures may be estimated from the work of Wu and Baeyens [11].

$$\frac{\bar{d}_{sv}\rho_g U_0}{\mu_g} = 7.3 * 10^{-5} * 10^{[8.24 log Ar - 8.81]^{0.5}} \tag{3}$$

Note 6

It is common for incinerators to have a tapered bed zone to allow for the large extra volume of gases produced by the evaporated water. This taper may be continued into the freeboard (or the freeboard diameter may be increased more sharply) to minimize the elutriation of fines. A high gas velocity in the bed gives a smaller bed diameter but leads to several disadvantages:

- the coarse inert particles are ejected at high velocity by the bursting bubbles and unless the freeboard is very high some will be carried out.
- the injected fines will be carried out of the bed zone rapidly and although their residence time in the incinerator can be increased by having a large freeboard, much of the combustion would take place above the bed rather than in it.

There is a lack of data both on the ejection of coarse particles and on the elutriation of fines injected into a bed of coarse solids. For the present we may note that in practice superficial velocities in the bed are normally limited to < 2 m/s and less than 1 % of the bed weight has to be added daily.

Note 7

Ash burn-out and freeboard design are considered in the paper by Baeyens and Geldart [3]. Using the shrinking particle model with ash flaking for the combustion of small sludge particles entrained above the fluidized bed. In doing so for all particles with a terminal velocity less than U_{fb}, the superficial gas velocity in the freeboard, the following expression was derived for the burn-out lengths:

$$L = 4.6 * 10^{8} U_{fb} \bar{d}_i^2 - 4.8 * 10^{15} \bar{d}_i^4 \qquad (4)$$

where $\bar{d}$ is the initial size of a particle whose terminal velocity is less than U_{fb}. The length L is expressed in meter. The solution of (4) is given graphically in Figure 4 for particle sizes which would just be elutriated by various values of U_{fb}. The height of the freeboard should obviously be larger than the burn out length L. Freeboard heights for various commercial incinerators are shown on the same figure for comparison.

Commercial designs need to be conservative and provide more than adequate freeboard heights (Figure 4); consequently the combustibles elutriated with the ash are negligible [12].

3.3 Conclusions

A design procedure is proposed for fluidized bed incinerators; in particular equations are given relating the gas velocity in the freeboard to the freeboard height required for complete burn-out of combustible particles of sludge. Freeboard designs of various commercial incinerators are compared with the model predictions and give reasonable agreement, however more plant data are essential to give greater confidence in design.

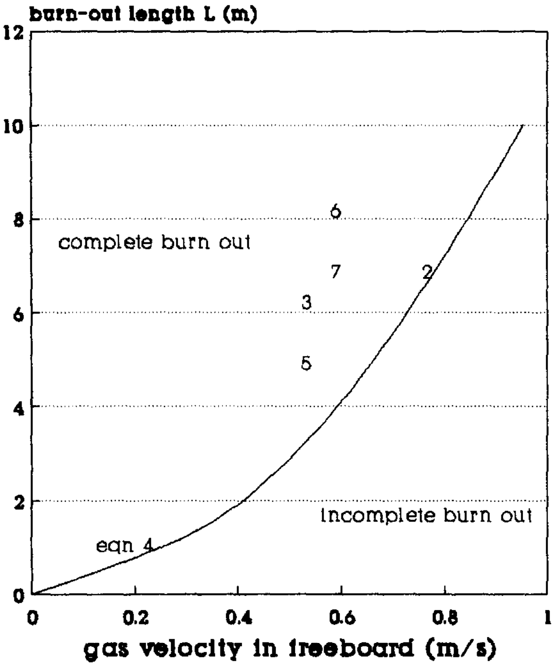

Figure 4. Theoretical burn out length vs freeboard velocity (Numbers relate to the freeboard heights for units listed)

commercial unit	1	2	3	4	5	6	7
D (m)	2.5	2.1	1.7	0.6	2.5	3.3	3.3
T (°C)	800	750	800	720	800	800	850

4 Beneficial utilization of incinerator ash

4.1 General comments

As indicated before, the cost of disposal for incinerator ash, which represents approx. 50 % by weight of the initial dry solids content is extremely high.

If by the year 1995, Flanders has to dispose of some 50000 ton/year of ash and provided sufficient landfill sites for industrial waste are available, this will represent an annual cost in excess of 20 million $ /year. The future of sludge incineration is therefore to a large extent conditioned by a better re-use of the incinerator ash.

4.2 Potential routes for utilization

Although research in the field is relatively new, a general trend can already be put forward.

Table 3 summarizes various sludge handling routes according to the products obtained and ways of potential utilization. Oshima [2] initiated this idea of beneficial re-use of incinerator ash.

Currently, research is being conducted in the specific fields of utilization in clay pipes [13], with external strengths some 10 % lower (for 6 % ash added) of the value for clay pipes with no ash added, and water absorption levels of 0.5 % above the clay pipe 5.5 %.

Due to the high concentration of alkali, the use of ash for soil stabilization purposes is currently being investigated for various road projects. Results are yet unknown.

The report by Yuki [14] is extensive with respect to sludge smelting and slag utilization. Artificial light-weight aggregates produced by sintering processes have been produced in demonstration projects of Tokyo and Nagoya.

Evidently more research is required to fully prove the beneficial utilization not only by demonstrating that added ash does not adversely affect the properties of the final product, but mainly by fully proving the economic feasibility of the processing. A challenge for the environmental engineer and a priority target for immediate sewage-research.

Table 3
Potential sludge utilization routes

Sludge form		Process		Product		Utilization
thickened sludge	→	digestion	→	medium kJ-gas	→	power generation
					→	heat
mechanically dewatered sludge (domestic nature)	→	none	→	dewatered sludge	→	agricultural use (fertilizer)
	→	drying	→	dried sludge	→	fuel
					→	fertilizer
	→	digestion	→	compost	→	fertilizer
Incinerated ash	→	none	→	→	→	soil stabilization
			→	→	→	asphalt filler
			→	→	→	admixture to cement or concrete
	→	sintering and and granulation	→	granulates	→	aggregates

Symbols

$\bar{d}_{sv}$	surface / volume particle diameter
$\bar{d}$	size of the burning particle at any time
d_i	size of initially elutriated particles
D	diameter of fluidized bed at distributor
D_{fb}	diameter of the freeboard
g	gravitational constant
L	burn-out length according to equation (4)
H_{fb}	height of the freeboard
T	temperature
U, U_0, U_{fb}, U_t	superficial velocity of gas, at incipient fluidization, in the freeboard, and at terminal conditions
ρ_g, ρ_p	density of gas and particle
μ_g	viscosity of gas
Ar	Archimedes number = $\frac{\bar{d}_{sv}^3 \rho_g(\rho_p-\rho_g)g}{\mu_g^2}$

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