TECHNICAL REPORT

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Sludge recovery, recycling, treatment and disposal — Guidance on thermal treatment of sludge

Valorisation, recyclage, traitement et élimination des boues — Lignes directrices pour le traitement thermique des boues

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 275, *Sludge recovery, recycling, treatment and disposal*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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Introduction

Sludge treatment and management is globally a growing challenge for most countries:

— sludge is a by-product of water treatment process produced in large quantities as new wastewater treatment facilities are built and the existing ones are upgraded to keep up with the population growth;

— sludge treatment and disposal constitutes one of the most significant costs associated with water and wastewater treatment;

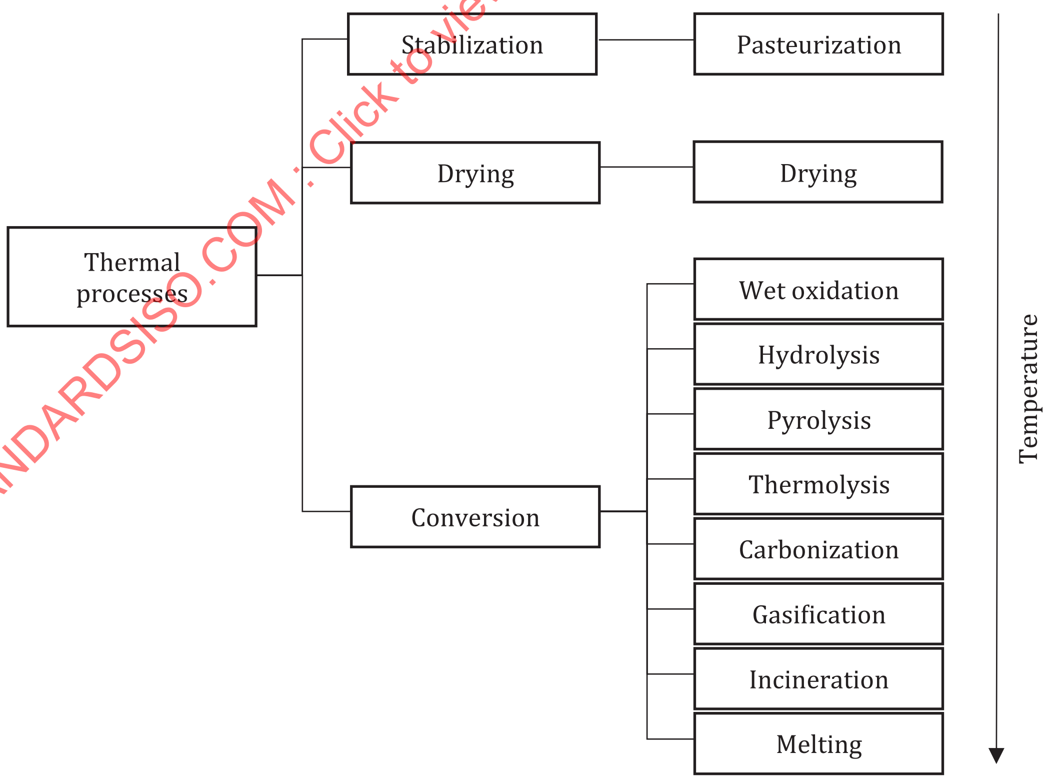
— stricter regulations on conventional outlets such as beneficial agricultural land, composting, landfilling require more treatment due to concerns about the long-term impacts on public health and environment;

— sludge is now being considered as a source of renewable energy, and also a source of valuable components such as carbon and nutrients.

The growing trend to recover energy and resources from waste sludge and stricter regulations on outlets have created interest in a number of thermal treatments and may meet, under certain conditions, the circular economy principles.

The objective of this document is to pragmatically present the methods for thermal treatment of sludge by covering the different process fundamentals, the associated technologies and operational aspects, the management of energy, valuables and residues, the aspects related to impacts and integration of installations referring to them.

Figure 1 highlights the thermal processes covered according to their main function and operating temperature.



NOTE The processes listed in the right column and connected to conversion and drying as main functions also achieve the sludge stabilization.

Figure 1 — Thermal processes covered by this document

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Sludge recovery, recycling, treatment and disposal — Guidance on thermal treatment of sludge

1 Scope

This document describes good practices for the incineration and other organic matter treatment by thermal processes of sludges.

Thermal conditioning is excluded.

This document applies to sludges specifically derived from:

— storm water handling;

— night soil;

— urban wastewater collecting systems;

— urban wastewater treatment plants;

— treating industrial wastewater similar to urban wastewater.

It includes all sludge that may have similar environmental and/or health impacts but excludes hazardous sludge from industry and dredged sludge.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
melting
thermal treatment which makes sludge or ash temperature raising over melting point of sludge inorganic substances

3.2
drying
thermal treatment for evaporating water from dewatered sludge to control water content by heating

3.3
carbonization
part of *pyrolysis* (3.4), focusing on production of a solid secondary resource so-called bio-charcoal

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3.4
pyrolysis
thermal treatment without supply of oxygen

[SOURCE: CEN/TR 16788, 3.4]

3.5
gasification
thermal treatment with less than the stoichiometric supply of oxygen or air (partial combustion)

3.6
char
combination of non-combustible materials and carbon produced from devolatization, *gasification* (3.5), *pyrolysis* (3.4) or *carbonization* (3.3) process

3.7
bio-charcoal
biochar
solid secondary resource, generated from carbonization (or pyrolysis) process

3.8
thermal treatment
treatment in which heat is applied to remove moisture, microbial content and organic compounds

3.9
thermal process
technique for the application of *thermal treatment* (3.8)

3.10
combined treatment
treatment of sludge and other waste in the same device

3.11
furnace
enclosed chamber where combustion of organic matter takes place

3.12
boiler
specific part of the thermal treatment plant where heat exchange takes place in view of recovering heat and energy

3.13
flue gas treatment
any physical or chemical process aimed at cleaning the gas emission resulting from the *thermal treatment* (3.8) with regard to their discharge into the atmosphere

3.14
bottom ash
combustion residue collected at the bottom of a combustion furnace

3.15
fly ash
solid material that is entrained in a flue gas stream

3.16
energy recovery
use of combustible waste as a means to generate energy through thermal treatment with recovery of heat

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3.17
recycling
activity in a production process to process waste materials for the original purpose or for other purposes, excluding *energy recovery* (3.16)

3.18
slag
partially glassy by-product obtained by cooling a mineral liquid phase

3.19
energy efficiency
amount of energy and/or heat recovery in relation to the energy content of input material

3.20
wet oxidation
wet air oxidation
aqueous-phase oxidation of organics under pressure, using either air or oxygen as the oxidant

3.21
syngas
mixture of gases (including carbon monoxide, hydrogen, methane, etc.) produced from *gasification* (3.5) or *pyrolysis* (3.4) process

3.22
combustion
chemical and exothermic reaction with full oxidation of combustible materials

3.23
autothermal conditions
conditions that keep combustion without auxiliary fuel and/or other external energy

3.24
paste-like sludge
sludge capable of continuous flow under the effect of pressure above a certain threshold and having a shear resistance below a certain threshold

[SOURCE: CEN/TR 15463, 1.2.b]

3.25
solid sludge
sludge having a shear resistance above a certain threshold

[SOURCE: CEN/TR 15463, 1.2.c]

4 Abbreviated terms

BAT	Best available technology
CFBF	Circulating fluidized bed furnace
DM	Dry matter
FBF	Fluidized bed furnace
GCV	Greater (or gross) calorific value
LCV	Lower (or net) calorific value
LOI	Loss on ignition

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MHF Multiple hearth furnace

MSW Municipal solid waste

PFBF Pressurized fluidized-bed furnace

SCR Selective catalytic reduction

SNCR Selective not catalytic reduction

3T Temperature, turbulence and (residence) time

5 Sludge properties

5.1 General

Sludge characterization for the assessment of thermal processes involves the evaluation of both technical and economic parameters. The main technical characteristics to evaluate the suitability of thermal process are DM or moisture content, calorific value, ash content. The main economic parameters are cost of processing, collection and transport, and the characteristics of the recovered materials and by-products.

5.2 Physico-chemical characteristics

5.2.1 General

The main physico-chemical characteristics to be taken into account are:

— DM (or moisture content);

— loss on ignition;

— calorific value;

— amount of grease, scum and screenings.

Physical consistency, together with rheological properties, also play an important role, especially as far as the design of feeding system is concerned.

5.2.2 Dry matter

The DM, or moisture content, is of primary importance for thermal processes because it strongly affects the LCV of organic material which decreases when the moisture content increases.

In thermal processing of sewage sludge DM is a parameter affecting both fuel requirement and exhaust gas production. Generally, any increase in DM is believed to be beneficial in the combustion for the reduction in fuel requirement. When the condition for autothermal combustion, at a given temperature, is reached the increase in DM corresponds also to a decrease in combustion gases production. Any further increase of DM beyond the limit of autothermal combustion involves a more abundant gas production, due to dilution air or water needed for the control of the combustion chamber temperature depending on design of incineration plant. However, the use of water, reduces the quantity of recoverable heat in the boiler.

5.2.3 Loss on ignition

The loss on ignition represents the portion mass escaping as gas as a result of the ignition of the dry mass of sludge.

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The loss of ignition is generally used as a measure of the volatile matter content but it should be noted that inorganic substances or decomposition products (e.g. H_2O, CO_2, SO_2, O_2) are released or absorbed and some inorganic substances are volatile under the reaction conditions.

It is measured by heating sludge in a furnace at 550 °C ± 25 °C (see Reference [4]) or 600 °C ± 25 °C (see Reference [18]) and expressed as percent of the dry mass. The loss on ignition can be used as an assessment of the organic part of the sludge, and is therefore related to its heat value.

The presence in the sludge of iron with oxidation during ignition from iron (II) to iron (III), and of calcium hydroxide or calcium oxide, when sludge is conditioned with lime, can involve decreasing of the loss on ignition value (see EN 15935).

5.2.4 Calorific value

Calorific value of sludge is a very important parameter for the evaluation of thermal processes, as it represents the heat quantity developed in the combustion process by the unit mass of material in standard conditions.

The calorific value can be expressed as (see EN 15170):

— GCV at constant volume which is absolute value of the specific energy of combustion, in Joules, for unit mass of a solid sludge burned in oxygen in a calorimetric bomb under the conditions specified. The products of combustion are assumed to consist of gaseous oxygen, nitrogen, carbon dioxide and sulfur dioxide, of liquid water (in equilibrium with its vapour) saturated with carbon dioxide under the conditions of the bomb reaction, and of solid ash, all at the reference temperature;

— LCV obtained by calculation from the gross calorific value provided that either the hydrogen content of the sludge or the amount of water found in the combustion test can be determined.

Sludge usually contains much water, combustible and incombustible solids. Therefore, their calorific value, especially on the “as received” basis is quite low.

The calculation of calorific value of sludge can be expressed per LOI (loss on ignition) or DM.

Typical calorific values of municipal wastewater sludge range from 22,1 MJ/kg LOI to 24,4 MJ/kg LOI (anaerobically digested primary) to 23,3 MJ/kg LOI to 27,9 MJ/kg LOI (raw primary). Secondary sludge displays values between 20,7 MJ/kg LOI and 24,4 MJ/kg LOI.

Given typical values of organic matter content (LOI), the calorific value of sludge would generally be in the range of 12 MJ/kg to 17 MJ/kg DM for non-digested sludge, 10 MJ/kg to 12 MJ/kg DM for digested sludge.

GCV and LCV values can be calculated according to the standard method EN 15170, while the procedures for the theoretical calculation of GCV and LCV are reported in Annex A.

5.2.5 Grease, scum and screening

Grease, scum and screenings can be thermally treated together with sludge but generally they pose several problems.

Screenings clog feed mechanisms for certain types of furnace and therefore grinding or shredding is advisable before feeding. Screenings also contain bulky and incombustible materials, which create problems in the ash disposal system.

Skimmed material generally contains more than 95 % moisture and therefore should be dewatered to at least 25 % solids before treatment. Skimming is difficult to handle in the dewatered state due to its viscosity and a heating process to 70 °C to 80 °C is generally requested to get skimming pumpable. After dewatering, scum solids should be ground to a size not exceeding 6 mm. GCV of skimming and screenings are in the range 37 000 to 44 000 kJ/kg DM and 23 000 to 25 600 kJ/kg DM, respectively.

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Quantities of screenings are strictly dependent on the screen openings. They can vary in the range of 3×10^{-6} m^3/m^3 to 40×10^{-6} $m^3/m^3$of sewage for openings of 12 mm to 25 mm (the upper limits apply to the reduced openings). As dewatered sludge production can be approximately evaluated in 1 l/m^3 of sewage, the screenings production can be accounted in approximately 0,2 % to 4 % in mass of sludge production, considering that the density of wet screenings is 640 kg/m^3 to 1 000 kg/m^3.

Quantities of scum are very much dependent on the quality of the sewage and on the collecting system in the wastewater treatment plant. The highest values can be as high as 17 g of DM/m^3 of sewage which means up to 1,7 % of sludge production. At a concentration of 25 % this value increases to 6,8 %.

The quantity of any added material, especially grease, scum and screening, is limited by the capacity and the efficiency of the gas treatment.

5.2.6 Physical consistency and others

The physical consistency of the sludge influences the selection and design of thermal processes.

Therefore, the evaluation of specific parameters giving information on this aspect (e.g. flowability, solidity, piling behaviour) appears useful in this designing step (see Reference [2]).

Other characteristics influencing thermal processes are particle size, bulk density and morphology.

5.3 Chemical and microbiological characteristics

5.3.1 General

The main characteristics to be taken into account are:

— sulfur;

— phosphorus;

— nitrogen;

— chlorine and other halogens;

— organic micro pollutants;

— trace elements (especially mercury);

— pathogens.

The presence of the above-mentioned chemicals should be known in order to prevent or minimize toxic emissions (gaseous, liquid, solid) from thermal processes.

Typical elemental composition depends also on the type of sludge, primary, activated or digested primary sludge (see Reference [13] for more details).

5.3.2 Sulfur

The sulfur content of sewage sludge ranges generally from 0,5 % to 2,1 % of DM.

In anaerobic digestion, sulfate is converted to sulphide by sulfate reducing bacteria. Some of it precipitates with iron and other metals as insoluble sulphides, while some other is stripped as hydrogen sulphide and is transferred to the biogas stream from which it can be removed by scrubbers. The amount of residual sulphides in anaerobically digested sludge is proportional to the metal content in the raw sludge. If sludge is not treated anaerobically, most of the sulfate remains in solution as such. If sulfate containing compounds are used as inorganic conditioners in thickening and dewatering, sulfur content increases. Sometimes, this can affect the cost of acid gas removal (e.g. in flue gas desulfurization). Because a fraction of the sulfur is present in the oxidized sulfate form, not all of this sulfur is converted

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to sulfur dioxide during combustion. Sulfur dioxide then combines with moisture, either in the waste gas treatment system or in the atmosphere, to form sulphuric and sulphurous acids.

5.3.3 Phosphorus

Phosphorus may be present in sewage sludge in concentration ranging from 1 % to 16 % DM.

However, phosphorus concentration in dry sludge can be widely changed, depending on wastewater treatment system prior to sludge treatment. This concentration mainly depends on the phosphorus load in the wastewater system and on the level of phosphorus removal accomplished in the treatment plant.

During combustion phosphorus and phosphorus compounds are converted to calcium phosphate which can be present in the furnace ash up to 15 % mass fraction of P_2O_5 in certain conditions; therefore, combustion ashes represent a useful source of phosphorus and its recovery should be considered.

5.3.4 Nitrogen

Nitrogen content of sewage sludge ranges from 2 % to 12 % of DM; typical values are around 5 % to 7 % of volatile solids in a mixed primary and secondary sludge. Organic nitrogen can be converted during combustion to molecular nitrogen or to NO_x, depending on the temperature and atmosphere inside the furnace. NO_x formation from fuel bound nitrogen can be controlled by restricting the air flow to the minimum excess above the stoichiometric requirement and by staging the air flow to the furnace (see 8.4). Nitrous oxide, N_2O, is generated as a result of reaction in thermal oxidation processes, which has approximately 300 times as high as CO_2 in terms of greenhouse gas effect.

5.3.5 Chlorine and other halogens

Organic and inorganic chlorine compounds play an important role in the combustion processes after tendency of the chlorine radicals to bind active radicals, like O*, H*, OH*, RO*, thus determining a decrease in the combustion rate with potential formation of toxic compounds. Chlorine and other halogens are also responsible for the presence in the exhaust gases of undesirable acidic compounds inducing corrosion problems especially at high temperatures. The presence of organic chlorine in sewage sludge is generally negligible (less than 50 mg/kg DM) but the concentration of inorganic chlorine may exceed some units per cent dry mass depending on the chlorine content in the sludge water and on the use of inorganic conditioners. The agroindustry sludge, similar to sewage sludge from food and/or beverage transformation and production, do not contain organic chlorine. As for sewage sludge, inorganic chlorine can be present in such sludge after the use of $FeCl_3$ as conditioning agent.

Bromine can exert similar effects as chlorine but the organic compounds are more easily formed and they can also be more easily destroyed at high temperatures.

5.3.6 Organic micro pollutants

Although the presence of biopersistent organic micro pollutants (such as chlorinated hydrocarbons, phenols and polyphenols, polychlorinated biphenyls, pesticides and polycyclic aromatic hydrocarbons and pharmaceuticals) in sewage sludge may be in some cases noticeable, they generally do not pose relevant problems in thermal processing.

Formation of dioxins can be a serious problem depending on the gas treatment and the temperature of incineration. Dioxins are rarely formed in sewage sludge mono-incineration process as the concentrations of dioxin precursor and unburned carbon are very low. Dioxins can be formed again (*de novo* synthesis) during the gas treatment, especially in the range of temperature 200 °C to 600 °C, for sludge with a high content in organochlorine compounds, this can be avoided by a rapid quench of the exhaust gas. Significant formation of particularly stable compounds has been evidenced in oxygen-deficient environments. However, rapid quenching is not necessary when the concentration of chlorine is low. Different reviews on quality of sewage sludge are available (see Reference [19]).

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5.3.7 Trace elements

The presence of trace element, such as mercury, arsenic, lead, cadmium and zinc, in sewage sludge should be considered for their tendency to be transferred in the gaseous phase. Except for mercury, they may be concentrated in fly ashes collected by commonly used particulate control devices like impingement separators, cyclones, bag filters, ceramic filters and electrofilters. Mercury generally escapes with flue gases but can be condensed in scrubbers or captured by activated carbon filters.

Trace elements are generally present in sewage sludge at variable concentrations depending on the proportion of industrial effluents in the wastewater. Table 1 shows the typical concentration range of trace elements.

Table 1 — Trace elements in sewage sludge ashes (DM)

Values in mg/kg

	Min.	Max.	Mean	Median
As	4,2	124,0	17,5	13,6
Cd	< 0,1	80,3	3,3	2,7
Co	7,3	83,5	28,1	20,7
Cr	58	1502	267	159,7
Cu	162	3467	916	785
Hg	0,1	3,6	0,8	0,5
Mn	334	6 488	1 914	1 307
Mo	7,5	112	25,3	20,0
Ni	8,2	501	106	74,8
Pb	< 3,5	1 112	151	117
Zn	552	5 515	2 535	2 534

5.3.8 Pathogens

Sewage sludge contains a mixture of different organisms, both saprophytes and pathogens. Most of microorganisms originate from human faeces. Main pathogenic organisms found in sewage sludge belong to the groups of enteric bacteria, parasites, viruses and fungi. Their concentrations depend on the wastewater treatment method and the physico-chemical processes the sludge went through. Their concentrations depend on the wastewater treatment method and the physico-chemical processes the sludge went through[11].

Sludge reintroduction in natural systems (land application) involves the adoption of precautionary quality criteria especially on the limit values for pathogens to prevent harmful effects on environment and human health.

6 Thermal processes fundamentals

6.1 General

This clause summarizes fundamentals related to each technology by covering:

— the phenomena involved: reactions, reactants, products;

— the requirements and optimal conditions for application;

— the expected quality on sludge/products quality;

— the possible positioning in the sludge treatment line.

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6.2 Drying

Thermal drying is a process in which thermal energy is delivered to the sludge in order to evaporate water. Sludge drying process reduces the mass and the volume of the product, making its storage, transport, packaging and retail easier and also enables further energy-efficient thermal treatment.

Water present in sludge may be of the following types.

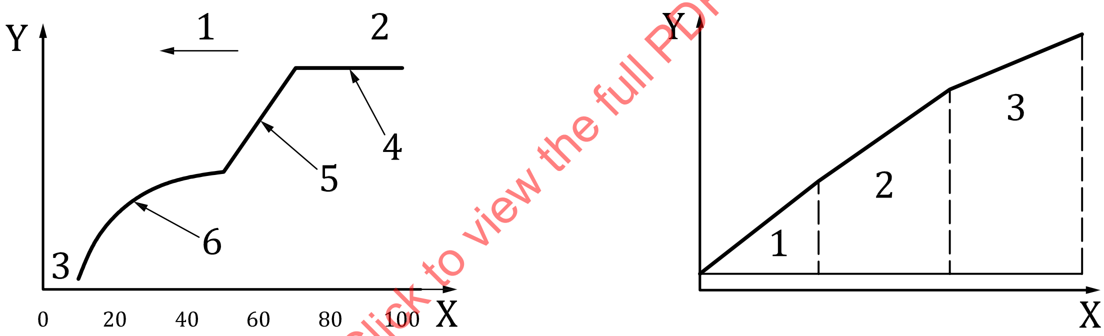
— Free water

Free water includes two subcategories. On the one hand supernatant water which is removable by natural gravity and thickening devices, and on the other hand bulk water which is trapped in flocs removable by dewatering devices.

— Bound water

Bound water is only removable by thermal processes and could be divided in three subcategories: internal or capillary water, surface water and chemically bound water.

Through the process, the sludge passes by several phases (see Figure 2). The number of these phases' changes according to the sludge quality and depends on the implemented drying method and the operating conditions. The different phases relate to decreasing evaporation rate when moisture content falls.



a) **Evaporation rates** b) **Physical changes**

Key

X moisture content (%)
Y evaporation rate
1 time
2 start
3 end
4 free water
5 interstitial water
6 surface water

Key

X time
Y dry solid contents
1 wet zone
2 sticky zone
3 granular zone

Figure 2 — Status changes during sludge drying time

Dried sludge has solid content usually greater than 90 % when drying is applied as final treatment. When sludge drying is applied prior to incineration, the solid content of dried sludge is generally 60 % to 70 %. Drying achieves sludge hygienization.

Under atmospheric pressure, water evaporation starts at 100 °C. Evaporation of 1 kg of water at 100 °C requires 2 257 kJ (0,63 kWh). Energy requirements in addition include the energy needed to increase

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the sludge temperature to slightly above 100 °C, plus energy losses in the drying system. Consequently, energy demands for all dryers range from 0,7 kWh/kg to 1,4 kWh/kg evaporated water.

The exchanges of mass and heat between sludge and air are essential for the drying process. The heat exchange is achieved through radiation, convection, conduction and mixture thereof.

Drying constitutes an important stage among the sludge management options.

— It reduces the volume of sludge and consequently decreases the cost of handling, transport and storage of the final product which is in addition sanitized.

— It increases the calorific value of the sludge which permits to use it, as a fuel or a co-fuel in cement kilns, in coal-fired power plants, municipal waste incinerators and sludge incinerators or other thermal treatments.

The waste to energy approach is currently a growing solution for sludge management.

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6.3 Hydrolysis

Thermal hydrolysis disintegrates the cell structure of bacteria into an easily digestible and dewaterable product by applying temperature.

It involves the application of heat above high temperature for a defined time period. One can distinguish thermal hydrolysis and thermal pressure-mediated hydrolysis. The pressure greatly favours the release of both carbohydrates and proteins.

The optimal temperature is approximately 170 °C for a time period of 20 min to 40 min and a pressure in the range 600 kPa to 1 500 kPa.

The reactions result in two sets of impacts depending on the temperature applied. Details are provided in Table 2.

Table 2 — Impacts of temperature application on sludge quality

For temperature up to optimum temperature range	For temperature beyond optimal temperature to sub-critical water range
— Improves downstream sludge anaerobic digestibility, thus biogas production and higher digester loading rates — Improves dewaterability — Decreases apparent viscosity — Decrease pathogenic content — Increases solubility of carbohydrates — Increases solubility of proteins, thus ammonia and alkalinity — Has negligible influence of solubility of lipids — Reduces average particle size	— Decreases downstream sludge anaerobic digestibility — Significantly increases production of refractory material and colour — Further reduces apparent viscosity — Further improves dewaterability

The temperature increase is achieved using steam. The steam demand is determined by the energy required to heat up the sludge from the inlet temperature to the outlet conditions and by the need to make up any system losses. The thermal energy required is approximately 0,3 MWh/TDS under optimal conditions. It varies according to influent sludge temperature, temperature difference, sludge physical properties.

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6.4 Incineration

Incineration (or combustion) is an oxidation reaction carried out at high temperature which makes it possible to reduce both the mass and volume of the materials being treated by reducing them to ash, while taking advantage of their inherent energy potential. The contained water, converted into vapour, and the organic matter converted into combustion gases are discharged into the atmosphere after treatment.

The reaction of oxygen with carbon, hydrogen and sulfur yields energy and products of combustion, namely, carbon dioxide (CO_2), water (H_2O) and sulfur dioxide (SO_2). Organic nitrogen is preferentially converted to nitrogen gas but a certain amount (2 % to 7 %) can also be further oxidized to nitrogen oxide (NO) and to nitrous oxide (N_2O).

The nitrogen in the air is also candidate to be converted to oxides of nitrogen (NO_x). This phenomenon begins to be noticeable at temperatures higher than 1 100 °C and increases with any further increase of temperature.

The reactions taking place are:

$$C + O_2 \rightarrow CO_2 + 393{,}5 \text{kJ/mol} \; (\Delta H°)$$

$$C_xH_y + (x + y/4)\, O_2 \rightarrow xCO_2 + y/2\, H_2O$$

Incineration produces a waste gas composed primarily of carbon dioxide (CO_2) and water (H_2O). Other air emissions include nitrogen oxides, sulfur oxides, etc. The inorganic content of the waste is converted to ash.

In the case of lack of oxygen (generally referred as starved-air combustion) the reactions are characterized as incomplete combustion ones, where the produced CO_2 reacts with C that has not been consumed yet and is converted to carbon monoxide (CO) at higher temperatures:

$$C + CO_2 + 110{,}5 \text{ kJ/mol} \rightarrow 2CO$$

The temperature achieved in the combustion process depends on the balance between the energy inputs and the energy outputs. The temperature should be higher than 850 °C during a 2 s time period.

All oxidizing combustion reactions require some excess air to ensure that the reaction proceeds rapidly to completion. Air required for combustion is mainly a function of time of stay, temperature and turbulence, commonly referred to as the “3Ts of combustion”. Generally, as turbulence is maximized, excess air can be decreased. Turbulence provides more opportunities of contact between fuel and oxygen and changes substantially for various types of combustion units. High efficiency burners may employ as low as 15 % to 30 % (1,15 to 1,3 times the stoichiometric amount of air) excess air while less efficient furnaces, like multiple hearth and rotary kiln furnaces, need 100 % to 125 % (2,00 to 2,25 times the stoichiometric amount of air) excess air at least. As excess air quenches the combustion temperature, it is desirable to minimize the quantity to be employed especially when auxiliary fuel is needed to sustain combustion. This effect can be reduced by air pre-heating. If insufficient excess air is added to the furnace or if one or more of the “3Ts” concepts are lacking, the combustion operation generates smoke and products of incomplete combustion, thus making incineration operation not acceptable.

The influence of cake concentration on fuel consumption, air requirements and flue gas production in incineration of sewage sludge is known. It has been shown that fuel consumption, air and flue gas production may be expressed as a linear function of cake concentration, with line slopes changing at the two points identified by the operating modes of (i) minimum concentration for autothermal combustion in the furnace, and (ii) minimum concentration for no air requirements in the afterburning chamber.

The ash consisting of inorganic material and incombustible organic substances, should be properly managed for recovery or disposal.

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Incineration comprises three principal phases corresponding to three conversion zones:

— the first step of combustion is the drying of the waste through contact with hot gases and decomposition into volatile materials which rapidly reach their ignition temperature;

— continuation of combustion as the waste moves or is moved through the furnace;

— gradual conversion into bottom ash which is then extracted and cooled down.

To avoid consuming make-up energy from fossil sources, it is desirable to achieve a thermal balance, i.e. so that the heat supplied by the combustion of the organic matter is sufficient to evaporate the water, to heat the combustion air and to raise all the combustion gases to a particular temperature (laid down by national regulations). Combustion in the system is then said to be in autothermal condition. In order to achieve autothermal conditions, sludge should be sufficiently dewatered or dried.

6.5 Pyrolysis

Pyrolysis is an endothermic thermochemical process where the organic matter in sludge is broken down in an environment lacking in oxygen compared to the stoichiometry required for the thermal oxidation of organic matter. It occurs in the absence of oxygen or in the presence of oxygen to such a small extent that pyrolysis reactions significantly prevail over gasification reactions. While pyrolysis reactions occur in gasification and combustion processes as precursor reactions, pyrolysis can also be operated as a separate process. It operates at temperatures of 400 °C to 800 °C. Pyrolysis treatment can be applied for a countermeasure for Hexavalent chromium (Cr^{6+}) emission control.

Pyrolysis essentially devolatilizes the fuel. The products from pyrolysis are a solid residue (mainly char) and a synthetic gas (syngas), while some of the volatile components form tars and oils that can be removed and reused. Char is a combination of non-combustible materials and carbon. The syngas is a mixture of gases (including carbon monoxide, hydrogen, methane, etc.).

The low temperature of operation eliminates the formation of SO_2 and NO_x and the gas and solid fractions produced can be used as a fuel.

The initial reaction is decomposition where organic components of low volatility are converted into other more volatile ones:

$$C_xH_y \rightarrow C_cH_d + C_mH_n$$

Reactions occurring during the early stages include condensation, hydrogen removal and formation of ring compounds that lead to solid residues from organic substances of low volatility:

$$C_xH_y \rightarrow C_pH_q + H_2 + \text{coke}$$

CO and CO_2 are produced and the interaction with water is possible if oxygen is available to the process.

The relative proportions of the three products, i.e. gas, liquid and char, depend very much on the reactor type and operating conditions. Basically, there are three types of pyrolytic reactions, i.e. conventional or Slow Pyrolysis, Flash or Fast Pyrolysis and Catalytic Pyrolysis.

In general pyrolysis processes are operated at temperature ranges of 400-700°C, lower than gasification or incineration processes (typically > 850 °C). Two general strategies can be distinguished, slow pyrolysis and fast pyrolysis.

Slow pyrolysis utilizes low temperatures around 400 °C over a long period of time to maximize char formation.

Flash/fast pyrolysis involves high heating rates (500 °C/s to 1 000 °C/s), moderate temperatures (450 °C to 500 °C), short gas residence times (<2 s), and rapid quenching of the vapours. It favours reduction of the solid waste volume and liquid yield depending on the temperature. The vapours are intensively condensed yielding a so-called bio-oil.

The addition of catalysts to the pyrolysis system (catalytic pyrolysis) further increases gas yield.

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The main parameters affecting the product distribution and energy content of pyrolytic products include temperature, heating rate, and residence time in the reaction zone. Most pyrolysis processes operate at atmospheric pressure. Vacuum pyrolysis can shorten the residence time of volatile products in the high-temperature zone, reducing the secondary decomposition and increasing the heat value of the gas products. Its implementation is however difficult in practice.

Pyrolysis is not effective in either destroying or physically separating inorganics. By-products containing heavy metals may require stabilization before final disposal. Volatile metals may be removed as a result of the higher temperatures associated with the process, but they are not destroyed.

6.6 Gasification

Gasification is the process of conversion by reactions with gasifying agents of a solid biomass feed material to a combustible gas (syngas). Gasification starts by providing external heat and a less than stoichiometric supply of oxygen or air to allow some combustion of the carbon to CO_2, which then reacts with solid carbon, to produce CO.

In contrast to combustion, for gasification addition of oxygen is at least limited (autothermal gasification) or completely absent (allothermal gasification, not to be confused with pyrolysis). With the first type, a portion of the gasifier feedstock is partially combusted in the reactor to sustain the process. With the latter type, an external energy source sustains the process.

Temperatures in a gasifier range from 500 °C to 1 700 °C depending on the process. This process works better if the sludge can be previously dried with a minimum DM content of 70 %. This needs a high effective pre-drying stage which could increase both capital and operational expenses. From an energetic perspective, it is sensible to use the heat generated through combustion of product gas in a combustion chamber to offset the heat demand of the dryer. Depending on the dried solids content of the sludge after mechanical dewatering and the heating value of the sludge, the heat demand can in many cases be completely satisfied.

The main reactions taking place during gasification are:

$C + O_2 \rightarrow CO_2$ (oxidation, exothermic)

$C + H_2O \rightarrow CO + H_2$ (water evaporation/ gas reaction, endothermic)

$CO + H_2O \rightarrow CO_2 + H_2$ (exothermic)

$C + CO_2 \rightarrow 2CO$ (Boudouard reaction, endothermic)

$C + 2H_2 \rightarrow CH_4$ (CH_4 formation, exothermic)

Main factors affecting the process are final temperature, residence time, rate of rise in temperature, gas atmosphere and pressure

Operation of the gasifier at slight overpressure (maximum 50 kPa) is adequate for heat and power applications. For autothermal gasification, a gasifying medium containing oxygen is supplied in a controlled manner so that sub-stoichiometric conditions prevail in the reactor. Gasification reactions liberate CO, H_2, CO_2, H_2O and CH_4. When air is used as a gasifying medium the resulting gas contains a significant portion of inert nitrogen and is thus classified as a LHV (low heating value) product gas. Typical heating values for a product gas generated from dried sewage sludge range from 3 MJ/m^3 to 5 MJ/m^3.

In principle, gasification offers some advantages over combustion; a gas has better burning properties in relation to a solid; the burning process is easier to control, needs less air excess, allows for simpler burner construction, causes no particle emissions, less air pollution and less fouling of the heat exchange equipment. Further, gases can be burned in internal combustion engines and can be easily applied in combined cycles.

Conventional gasification of sewage sludge also generates a solid residue (char) that still contains some volatile material and inorganic pollutants depending of the quality of the input material and process.

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The disadvantages with respect to incineration include relatively complex system, and variable costs; there is no clear evidence about the fate of heavy metals in conventional gasification systems. Commercial plants are available, see Annex C.

Sludges are generally pre-treated before gasification. For most pyrolysis applications, drying and size-reduction are required in the pre-processing steps. This may also include blending. The moisture content is a key parameter. Gasification runs best at moisture contents between 5 % and 10 % of water content. Thus, the thermal drying process represents a significant heat consumer in the thermal sludge treatment process. From an energetic perspective, it is sensible to use the heat generated through combustion of product gas in a combustion chamber to offset the heat demand of the dryer. Depending on the dried solids content of the sludge after mechanical dewatering and the heating value of the sludge, the heat demand can in many cases be completely satisfied.

Combustion and gasification processes may employ a pyrolysis process upstream of the main reactor as part of a staged thermal treatment process. The main advantage of a staged-combustion process is the generation of a homogenous gaseous fuel allowing for a more controlled combustion. Staged gasification processes for combined heat and power applications may use a pyrolysis reactor upstream of the gasifier in order to minimize the tar content of the product gas before combustion in a combined heat and power motor, thus increasing the overall energy conversion in the motor. The main difference between a separate pyrolysis process and staged-combustion or staged-gasification processes is that a char product is generated with the former, while the char is typically valorised in the latter applications, discharging an ash by-product.

6.7 Thermolysis

Thermolysis constitutes an extreme pyrolysis process as it takes place in the absence of any exogenous oxygen.

6.8 Carbonization

Carbonization is a general name of process that is focusing on production of a solid secondary resource so-called bio-charcoal and it has been used for production of wooden charcoal since long ago. When sewage sludge is heated under low or no oxygen supply, pyrolysis reaction is started by evaporating moisture content and releasing adsorbed gases and bio-charcoal that mainly consists of carbon is generated after completion of releasing synthetic gas (syngas or pyrolysis gas). The operation temperature is between 250 °C and 800 °C, depending on a type of reactor and a targeted calorific value of bio-charcoal. Products of carbonization process are bio-charcoal and syngas. For other characteristics, refer to 6.5.

6.9 Wet oxidation

Wet oxidation, also called wet air oxidation (WAO) is based on aqueous-phase oxidation of the organics in sewage sludge, using oxygen from either air or oxygen gas as oxidant

The oxidation reactions occur at a temperature above the boiling point of water (100 °C), but below the critical point (374 °C) above which is the domain of supercritical wet oxidation (SCWO). The oxidation reactions occur at temperatures of 150 °C to 320 °C and at pressures from 10×10^2 kPa to 220×10^2 kPa. Higher temperatures require higher pressure to maintain a liquid phase in the system.

For sludge, the oxidation takes place at 250 °C to 300 °C and 50×10^2 kPa to 100×10^2 kPa.

The process can involve any or all of the following reactions:

Organics + $O_2 \rightarrow CO_2 + H_2O$ + RCOOH (short chain organic acids)

Sulfur species + $O_2 \rightarrow SO_4^{2-}$

Organic Cl + $O_2 \rightarrow Cl^{-1} + CO_2$ + RCOOH

Organic N + $O_2 \rightarrow NH_3 + CO_2$ + RCOOH

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Phosphorus + $O_2 \rightarrow PO_4^{3-}$

6.10 Melting

Sludge melting also called "sludge vitrification" is the technology which melts inorganic matters (mainly its silica compound) in the sludge raising its temperature over melting point, typically found in the range 1 100 °C to 1 250 °C. Consequently, melting is performed in furnaces generally operated under 1 200 °C to 1 350 °C and up to 1 500 °C.

There are two application points of melting, which are: dewatered sludge after drying and ash from sewage sludge incineration.

Upon heating, moisture and organic matter in the sludge are evaporated and combusted like under incineration, furthermore low boiling point metals such as cadmium are also evaporated. From ash, low boiling point substances are evaporated and transferred to the flue gas. The evaporated substances are solidified again during cooling of the flue gas for heat recovery and detoxication.

Melting sewage sludge produces melt-solidified slag. Depending on the cooling method, slag is classified as granulated slag, air-cooled slag and crystallized slag. There are roughly two methods of cooling melted slag which are rapid cooling and gradual cooling. In case of rapid cooling, slag forms brittle granular and in case of gradual cooling, slag forms crush stone-like shape with a stronger hardness than rapid cooling. Both types of slag can be used for construction material such as road material and resource as concrete secondary product (see JIS A5031:2006) and fertilizer.

The melting process is more effective than the conventional incineration process for reducing the volume of sludge. The bulk density of slag is two and the half times that of the fly ash. Low boiling point substances are evaporated under such high temperature and induced from melting furnace as a part of flue gas. The evaporated substances are solidified again by cooling during flue gas heat recovery and flue gas treatment. Though the bulk density of incinerated ash might be around 600 kg/m^3 (as dry ash), that of the melting slag might be around 1 500 kg/m^3. In case of treating heavy metals contaminated sludge by chromium for example, melting technology can be applied for the purpose of stabilization that confined heavy metals into the slag. It is easier to treat the slag than the fly ash from incineration, and the hazardous substances are better fixed in the slag without leach.

6.11 Pasteurization

This process really achieves sludge disinfection by destruction or inactivation of pathogenic organisms contained in the sludge. Destruction is defined as the physical disintegration of the organism, while inactivation is defined as the cancellation of its ability to infect.

The survival of microorganisms is a function of a number of factors including the characteristics of their species, local temperature and antagonistic conditions. For a population of specific microorganisms, the lethal effect is gradual and the kinetics generally follow the exponential Chick's law of disinfection where the surviving fraction (Xt) is dependent on the starting population number (Xo) the treatment time interval (t - to) and the specific decay rate, k dependent on temperature:

$$Xt/Xo = e^{-k(t - to)}$$

Consequently, the requirement for pasteurization is that all sludge be held above a predetermined temperature for a minimum time period[12].

The process of pasteurization involves the heating of sludge to a relatively high temperature but below water boiling point and often below the point of protein denaturation. Pasteurization at 70 °C for at least 1 h is an effective approach to eliminate most pathogens under detection limits but the method fails to eliminate bacterial endospores using standard pasteurization procedures. For example, Salmonella is killed within 30 min in sludge heated up to 70 °C. Typically, conditions range from four hour-treatment at 55 °C to 30 min or longer at 70 °C for using the treated sludge on agricultural land to prevent any health or environmental risks from residual pathogens according to national requirements[15],[16]. Pasteurization differs from sterilization that uses much higher temperatures, usually at or above the

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boiling point of water. Ideally, pasteurization should be included either before or after the regular stabilization processes (digestion, composting, or liming) which are also able to lower to a certain extent the pathogenic microbial content and alter the sewage sludge so that it becomes a less effective medium for microbial (re)growth or recontamination and thus a product suitable for use as a crop fertilizer. Pasteurization is typically combined with subsequent anaerobic digestion which may be at mesophilic temperatures, which would result in the generation of energy rich biogas in the same facility to cover the energy requirements of the pasteurization stage.

Pasteurization is employed extensively in Western Europe.

7 Technologies

7.1 General

An overview of each device based on each fundamental technology listed in Clause 6 is described in this clause, including general design aspects and auxiliary equipment.

7.2 Drying

In general, the dryers used are based on those found in chemical and agro-processing industries. Thermal drying typically needs to be preceded by, or done in conjunction with a dewatering process, A typical drying system includes the dryer itself, materials handling devices and storage equipment, heat generation and transfer equipment, air movement and distribution equipment, emissions control equipment, and ancillary systems. Drying systems are characterized according to different methods for heat transfer to sludge which are convection, conduction, radiation heating. Multiple methods can be involved of heat transfer in hybrid systems which are generally categorized by their primary method of heat transfer. Depending upon the drying technology used, dried sludge is obtained in various forms (granules, pellets, fines) and densities.

7.2.1 Direct dryers

Dryers that use convection for heat transfer are also referred to as “direct” dryers in which the moisture from the sludge is removed by the carrier gas. In such systems, the heat transfer occurs thanks to the direct contact of hot air/mixture of air and exhaust gas with wet sludge. The hot air/gas is most often produced by a gas or oil-fired furnace at high temperature. The drying process produces vapour that is a mixture of steam, air, and released gases from the sludge. The vapour and gas mixture needs to be cleaned. The treatment of the condensate may be complicated due to the presence of ammonium hydroxide (NH_4OH) or volatile organic carbon (VOC). The dried sludge is separated from the hot exhaust gas, screened and processed for partial recycling back in some technologies to the dryer and routing to storage vessels. Intensive sludge recirculation implemented in some dryers enables to overcome difficulties due to the plastic phase occurrence but the uniformity of the mix and flow are difficult to control in connection with the sticky behaviour of the sludge. After cooling for condensation, the exhaust air/gas is partly (70 % to 90 %) recycled back to the dryer. The rest of the air/gas is treated in air pollution control equipment (filter or cyclone for dust removal, biofilter and thermal oxidation for odours and other undesired components) and then vented. The main direct drying units are rotary drum dryers, belt dryers and fluidized-bed dryers. The specific energy consumption ranges from 700 kWh to 1 400 kWh per ton of evaporated water. The working capacity usually ranges from 5 000 kg/h to 15 000 kg/h of evaporated water.

Representative schematic diagrams are shown in Figure 3 and Figure 4.

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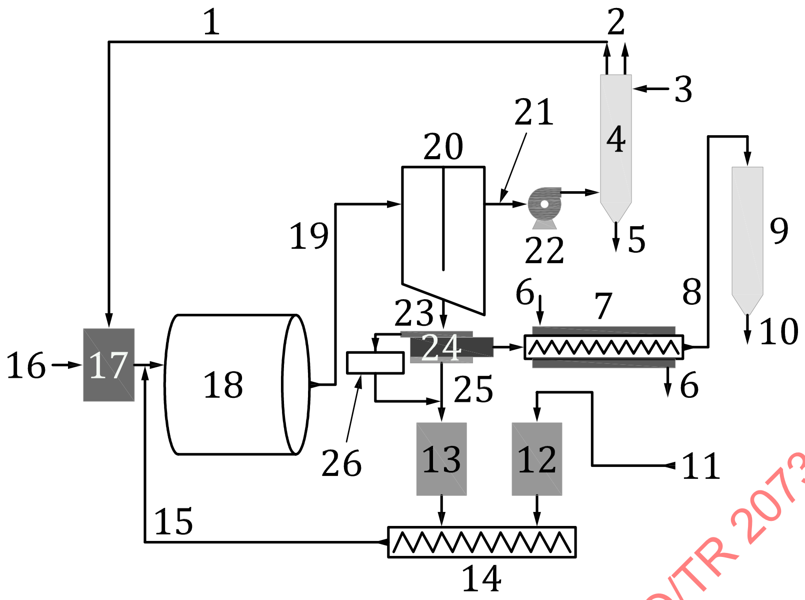

Key

1	recycle air	14	mixer
2	air exhaust to air pollution control	15	feed
3	cooling water	16	fresh air and fuel
4	condenser	17	furnace
5	condensate	18	drum dryer
6	water	19	dry solids and recycle air
7	product cooler	20	air/solids separator
8	cooled pellets	21	air
9	storage silo	22	fan
10	dried biosolids	23	dry solids
11	wet cake from dewatering system	24	screen
12	wet cake bin	25	recycled dry solids
13	recycle bin	26	crusher

Figure 3 — Rotary drum dryer system

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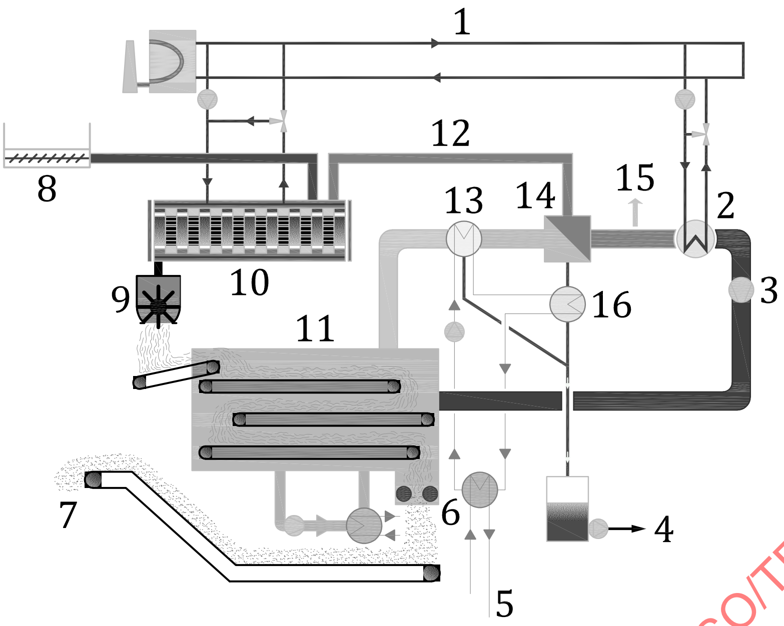

Key

1 heating medium (oil or stream)
2 re-heater
3 air fan
4 condensates
5 heat export
6 sizer
7 granules
8 sludge pump
9 chopper
10 thin film evaporator
11 belt dryer
12 heat recovery (vapour)
13 air cooler
14 condenser
15 air exhaust
16 post-condenser

Figure 4 — Belt dryer system

In drum dryer, the dewatered sludge with a dry solid content in the range of 20 % to 35 % is introduced via appropriate feeding devices into a revolving drying drum. The material flows away from the entry point through the drum internals which can largely vary. The drum dryer can be single pass or multi-pass. The residence time in the dryer depends on drum speed, drum inclination, flow rate of the drying gas and the storage device of the drum end.

The belt dryer is a lower temperature system compared to a rotary drum system. In contrast to the rotary drum system, the thermal fluid used is hot water or flue gas supplied to air heat exchanger. The belt drying system distributes dewatered sludge as a thick layer (4 cm to 15 cm) onto a horizontal perforated belt moving slowly to offer a high surface area exposure to the hot air. The sludge can be introduced and shaped by an extruder before entering the belt zone to increase again the exposure. The drying area can be divided into several sections equipped with air inlets to control at best the temperature in the range of 90 °C to 150 °C. The lower temperature belt drying system can utilize lower grade waste heat in addition to high temperature waste heat. Belt drying systems can have multiple belts to help minimizing the unit volume size. The rate of air recirculation is commonly over 90 %. The gentle sludge flow on the belt limits the dust generation. The condensate produced is extracted. Figure 4 shows a mixed arrangement in which the main hot air belt dryer is preceded by a thin layer drier. The indirect method is used to condense the vapour emitted during the first drying stage and the vapour's latent heat is recovered for use in heating the hot air loop acting as the second stage heat exchange fluid. This greatly reduces the dryer's energy consumption compared to other drying technologies.

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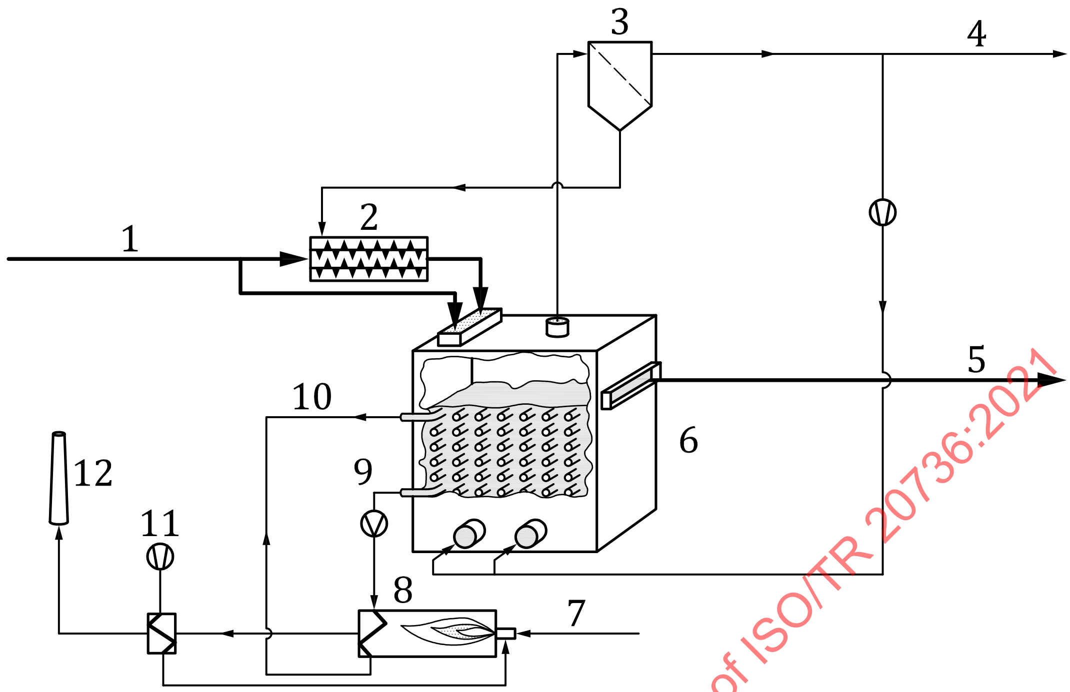

Key

1 dewatered sludge
2 mixer
3 solids separator
4 exhaust vapour treatment
5 dried sludge
6 fluidized bed dryer
7 oil/gas
8 burner
9 condensate
10 steam
11 air feed
12 exhaust gas

Figure 5 — Fluidized bed dryer system

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Other dryers using convection are of fluidized-bed type (see Figure 5). These operate on the basis of an upward air flow passing through the bulk of sludge. Dewatered sludge is directly fed into the fluidized bed first filled with dry granules. Fluidization gas is uniformly blown over the cross-section of the dryer generating a fluidized bed of dry granulates which are mixed at the same time. The granules become free-floating and at the same time mixed thoroughly. Granulation occurs upon water evaporation and particle movement in the dryer. The fluidized bed dryer itself consists of three main sections: a wind box with a gas distribution plate, a middle section which holds the heat exchanger immersed in the fluidized bed, a top dryer hood which separates particles lifted from the layer with the fluidization gas. This may partly deagglomerate the solid and turns it into a fine powder. The gas leaves the dryer carrying the evaporated water and the fine powder. The fine powder is separated in the cyclone and the evaporated water is condensed out of the gas stream in a scrubber-condenser. The dust is fed to a mixer with the inlet dewatered sludge. The dryer operates in a closed inert gas loop. The heat exchanger transfers all the required heat for evaporating the water coming along with the wet sludge. Steam or thermal oil is the usual transfer medium. The dry granules leave the fluidized bed unit through the discharge opening.

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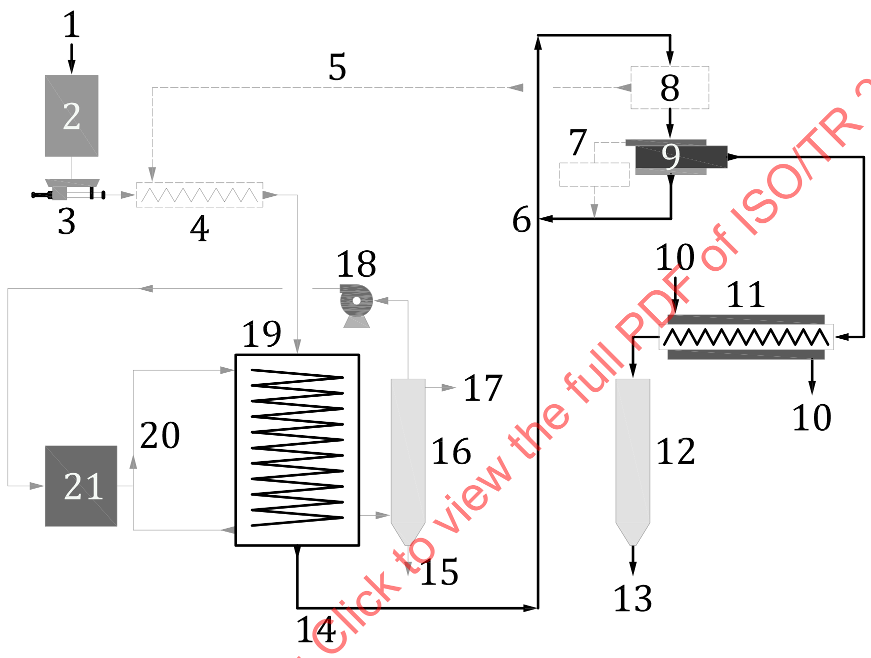
7.2.2 Indirect dryers

Systems that primarily use conduction for heat transfer are referred to as "indirect" dryers. In indirect dryers, metal walls separate the wet sludge from the heat transfer medium which can be steam, hot water or oil heated in a boiler fired with fossil fuel or biomass. The sludge is mechanically moved through the dryer. Its temperature is raised by contact with the heat exchange surfaces. Some types of indirect dryers are able to handle viscous fluids so that recycling of dry material is not required. Following the dryer, the material handling equipment is similar to that used in the direct system. The three main technologies used are: disc, paddle and thin film dryers. For all, a rotor whose design is key serves for sludge conveying. The specific energy consumption varies from 800 kWh to 1 000 kWh per ton of evaporated water with a specific evaporation rate more important than for convective drying. This range of dryer provide an evaporating capacity of up to 4 000 kg/h. A schematic diagram of a typical paddle drying system is shown in Figures 6 and 7.



Key

1 wet cake from dewatering system
2 feed bin
3 feed pump
4 mixer
5 recycled dry solids
6 dry solids
7 crusher
8 separation hopper
9 screen
10 water
11 product cooler
12 storage silo
13 dried biosolids
14 dry solids
15 condensate
16 condenser
17 cooling water
18 fan
19 indirect dryer
20 steam or thermal fluid
21 heater

Figure 6 — Typical paddle drying system

In the disc dryer, the rotor consists of a shaft with hollow discs shaped as plates and equipped with transport paddles. The discs are heated by thermal fluid injected into the rotor axis and distributed across the disks. The combined action of disc and stirring paddles ensures an excellent heat transfer and a slow progression of the sludge. Wiper and paddles are required to clean the disc surface. To avoid clogging, a part of the dry sludge might be mixed with the inlet dewatered sludge.

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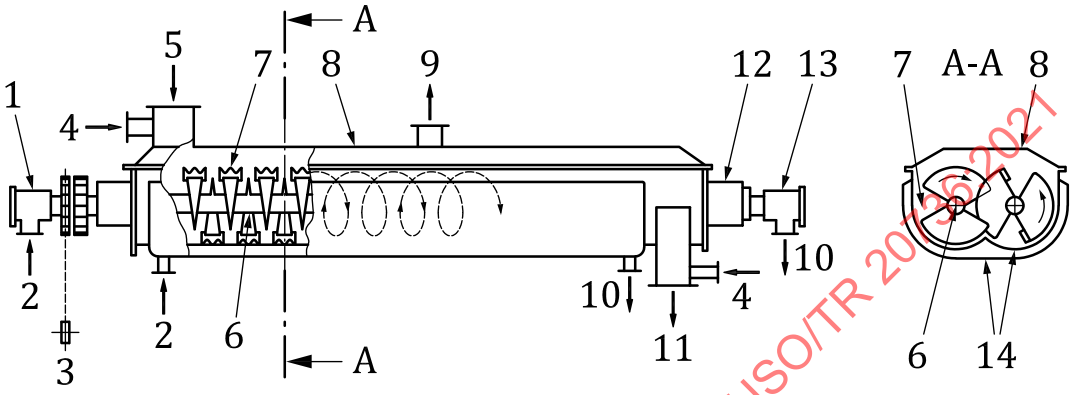
According to the principle of paddle dryer, two shafts bear hollow paddles and rotate in opposite directions. This overlap of movements ensures both a high shearing of the sludge and a self-cleaning of the system. Consequently, full drying can be achieved without sludge recycling paddle dryers (see Figure 7) usually equip with 1 to 4 rotating shafts with disk-shaped paddles. The shafts, the paddles and casing jackets are heated by the heat transfer medium (e.g. steam) and indirectly transfer the heat to sludge. As a heat source, middle pressure steam (0,7 MPaG to 0,9 MPaG, 170 °C to 180 °C saturated steam) is generally applied. The dried sludge of paddle dryer might be 60 % to 80 % in solid content.



a) Paddle side view system

b) Cross section of paddles

Key

1	rotary joint	8	top cover
2	steam inlet	9	evaporate
3	drive motor	10	drain outlet
4	air	11	dried sludge
5	sludge	12	bracket
6	shaft	13	rotary joint
7	paddle	14	casing jacket

Figure 7 — Typical paddle dryer system

Thin-film dryers (see Figure 8) use a horizontal cylindrical stator with a rapidly spinning rotor (peripherical speed of approximately 30 m/s of peripherical speed). The rotor is also equipped with a variety of blades with adjustable pitch. These take the sludge to the heated wall, where it forms a dynamic film of 5 mm to 15 mm thickness. Due to the excellent heat transfer in this thin film, the liquid evaporates quickly, resulting in a powdery, partially finely ground solid. As the thermal fluid is only fed on the double jacket of the housing, thin film dryers are less compact than other indirect dryers. The technical capacity of indirect dryer usually ranges from 750 kg/h to 4 000 kg/h of evaporated water and can reach 8 000 kg/h of evaporated water.

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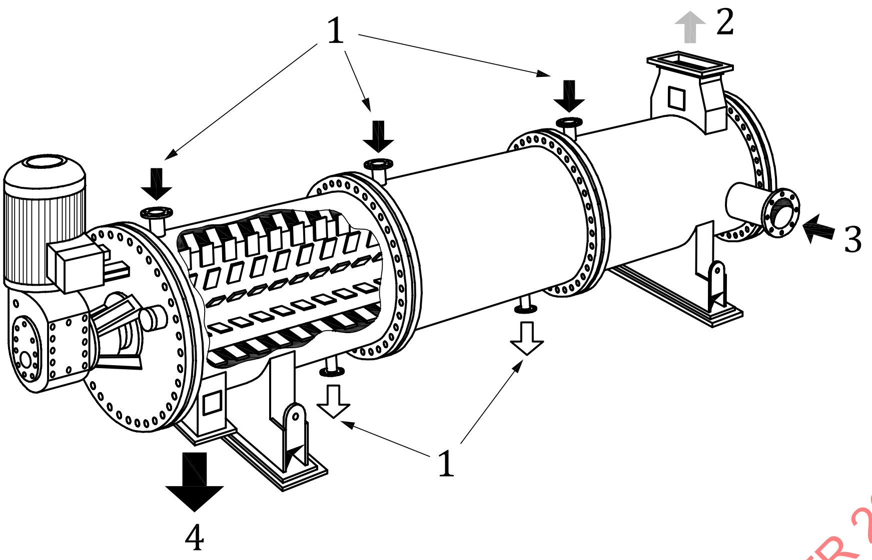

Key

1 heating medium

2 vapour

3 wet feed

4 dry product

Figure 8 — Typical horizontal thin-film drying system

7.2.3 Solar dryers

Solar drying systems use radiant energy from the sun. Drying is performed in open or closed greenhouses. Sludge is distributed uniformly in deep bed (40 cm to 80 cm) by mechanical means. The sun's radiant energy passes through the greenhouse transparent enclosure (walls and roof) to heat and evaporate moisture from the sludge. The greenhouse enclosure constitutes a semi-controlled environment, in which ventilation or wind produces air convection able to evacuate humid air and odorous compounds released to an odour treatment system. A mechanical system is commonly used to spread, turn, aerate and convey the sludge along the greenhouse length in order to renew the surface exposed and avoid formation of crust (see Figure 9).

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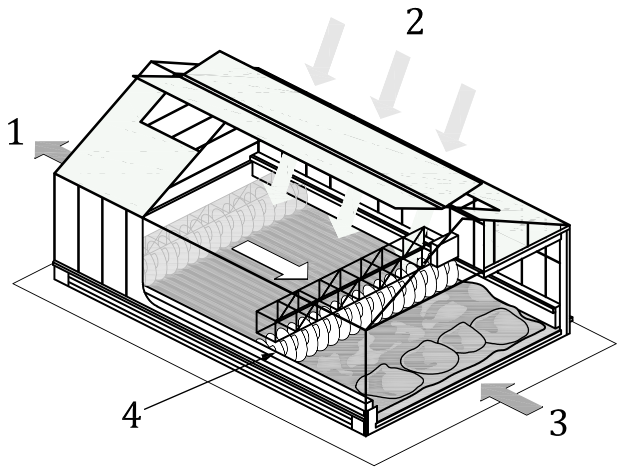

Key

1 dried sludge output
2 solar radiation
3 dewatered sludge intake
4 rotary scarifier

Figure 9 — Typical solar dryer system

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Solar drying systems are very sensitive to local weather conditions and require land available. Thermal heating through injection of fluids or using heat pumps can also be implemented into the concrete greenhouse floor to overcome these drawbacks. Solar drying processes can be designed are to provide solids content ranging from 35 % to 85 % with optimum at approximately 70 %. The sludge is then transformed into 1 cm to 4 cm diameter granules, free-flowing bio-solid with pathogenic content reduced. The total energy required typically varies between 30 kWh and 200 kWh per ton of water loss. There are multiple solar drying systems available and vary in their equipment supply and how they operate.

7.3 Hydrolysis

Thermal hydrolysis of sewage sludge involves the application of heat at above high temperature for a defined time period prior to anaerobic digestion. In thermal pressure-mediated hydrolysis, the heat is typically provided by live steam injection at design temperature under concomitant pressure (600 kPa to 1 500 kPa) which is then rapidly released. More usual thermal hydrolysis configurations use standard heat exchange. The optimal operating conditions involve a temperature around 170 °C in order to avoid the production of non–biodegradable by-products for a treatment duration between 20 min and 40 min. Typically, the inlet sludge is pre-dewatered to approximately 15 % to 18 % dry solids content. Further dewatering may cause heat transfer limitations as well as practical processing concerns.

A thermal hydrolysis process (THP) train includes pulper vessel, reactor, flash tank, pulper recirculation/reactor feed pump, digester feed pump, process gas cooler and process gas compressor skid.

The feed pumps send the pre-dewatered solids to the pulper vessels. The sludge is then pre-heated using steam recycled from the downstream flash tank. Sludge in the pulper vessel is mixed thanks to pulper circulation pump. Plant water can be added to the pulper circulation pump loop to reduce the pre-dewatered solids if necessary. The pulper circulation pump serve to homogenise the temperature and concentration of the solids in the pulper. The reactor feed pumps transfer sludge from the pulper vessel to the reactor. Following the reaction, thermally hydrolysed sludge (THS) is driven into the flash tank by excess pressure. The flash tank reduces the temperature of the sludge by recovering steam into the pulper vessel, and also functions as a reservoir for the digester feed pumps, which move solids to the digesters. Upstream of the digester feed pumps, plant water is added to the hydrolysed solids. This is done to adjust the DS content of the solids feed to the digesters as well as ammonia concentrations.

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The dilution system also cools the solids, reducing the temperature, which also reduces the wear on the digester feed pumps. Dilution water is set as a ratio or a given flow through a control valve. The off-gas and steam collected in the pulper vessel is considered foul gas due to malodorous state and water saturation. Process gas is passed through a process gas cooler (heat exchanger) to cool down the gas and condense moisture, with the condensate drained back to the pulper vessel. Cooled foul gas enters foul gas compressor skids to increase gas pressure. The compressed foul gas is fed into the digester feed system piping.

There are several benefits for thermal hydrolysis, like biogas production, volatile solids removal, dewatering efficiency and quality of liquors returns.

7.4 Incineration

7.4.1 Fluidized bed furnace

The fluidized bed furnace (FBF) is by far the dominant technology. Other types are the multiple hearth furnace (MHF), the rotary kiln furnace (RKF), the electric furnace (EF), the cyclone furnace (CF) and the grate furnace (GF). For sludge co-incineration, stoker type incinerators and power stations are commonly used.

It consists of a cylindrical refractory lined shell containing a sand bed fluidized during operation by air through a distributor system under plate or pipe installed below the bed. The temperature of the bed is controlled above 750 °C when incineration is applied after drying and about 700 °C when applied after dewatering. For dewatered sludge incineration, it is important to control the bed temperature above the combustion temperature of auxiliary fuel. For oil, it should be above 650 °C and for liquid natural gas, above 700 °C. A representative schematic diagram of FBF is shown in Figure 10.

Concerning the combustion air, the stoichiometric amount is that which should be injected into the furnace in order to provide the amount of oxygen required for achieving the combustion reactions. The different zones for introduction and distribution of the combustion air are particularly important. Refractory linings are very important because they are employed to prevent damage to the structural steel shell and to reduce heat losses. They should be designed and installed to comply also with “gas tight” parameters which can be critical especially in FBF. Anti-fire refractory materials such as alumino-silicate backed up by insulating brick is most commonly used. Properties of interest are for example resistance to chemical attack, hardness, heat conductivity, thermal expansion, bulk density, apparent porosity, mechanical strength, thermal shock resistance, chemical composition.

Construction materials used in the heat recovery section, should be carefully chosen, considering maximum operating temperature and actions exerted on them by different chemical species that can be encountered in combustion gases.

Process air distribution by nozzles is another key point in FBFs.

Sludge feeding for incineration can be achieved by:

— distributing onto a fluidized bed by feed system such as bulk fuel spreader or screw feeder,

— feeding to the fluidized bed through openings in the furnace top cover, or

— injecting into the furnace using screw pumps and injection lances at the fluidized bed level.

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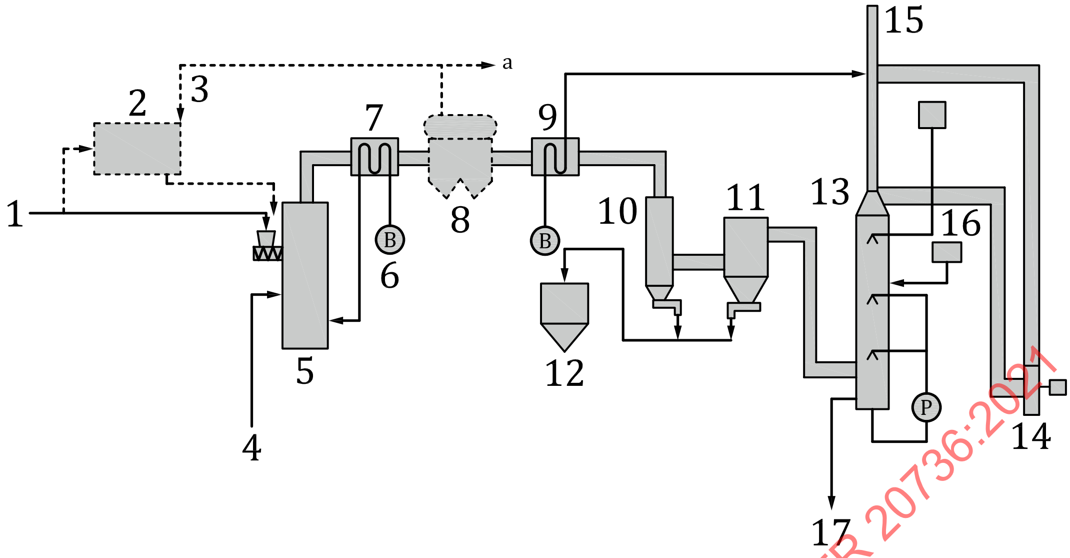

Key

1 sludge
2 dryer
3 steam
3a steam to turbine
4 fuel
5 fluidized bed furnace
6 fluidization blower
7 air heater
8 boiler
9 plume prevention air heater
10 quencher
11 bag filter
12 ash hopper
13 scrubber
14 induced draft fan
15 stack
16 NaOH
17 waste water

Figure 10 — Typical fluidized bed furnace system

As a pretreatment upstream incineration, drying might be adopted to reduce the fuel consumption. The heat source for dryer is recovered from flue gas. To utilize the heat of flue gas at maximum as recovered heat, heat recovery processes are adopted such as air heater (heat exchanger) and/or boiler. After the heat recovery, dust (ash) in flue gas is collected by a dust collector (e.g. bag filter/electrostatic precipitator/ceramic filter). Most of gaseous acidic substances are removed from flue gas by using a scrubber, and then flue gas is induced by an induced draft fan to a stack.

FBFs can have a cross section from 1,5 m to 9 m and height from 6 m to 16 m for a bed expansion of 1,5 to 2 times the fixed bed height. Excess air counts for 25 % to 100 %.

A cross section of a FBF is shown in Figure 11.

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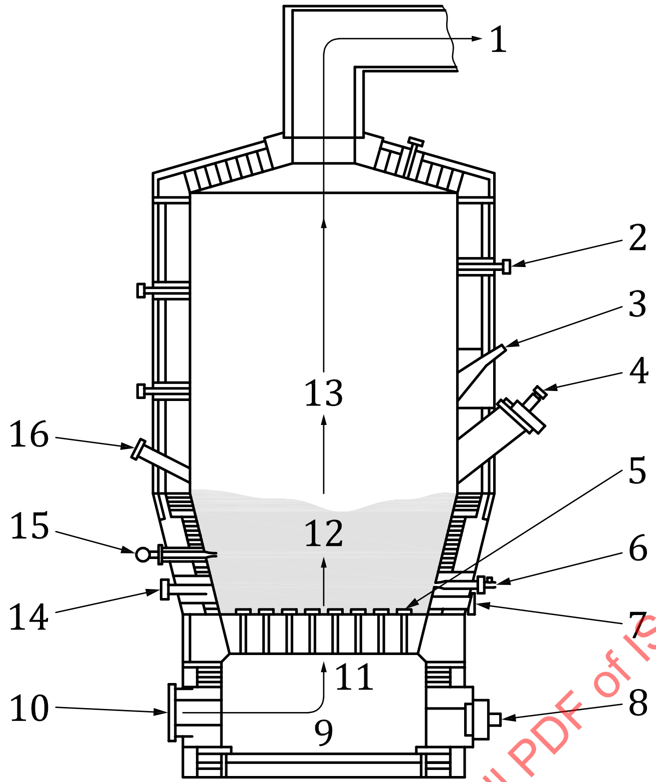

Key

1	exhaust and ash	9	Wind box
2	pressure tap	10	fluidizing air inlet
3	sight glass	11	refractory arch
4	burner	12	fluidized sand bed
5	tuyeres	13	freeboard
6	fuel (and water) injection lances	14	sludge inlet
7	pressure tap	15	thermocouple
8	start-up preheat burner for hot wind box	16	sand inlet

Figure 11 — Bubbling fluidized bed furnace (typical cross section)

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Advantages of FBFs are low excess air requirement, due to the high turbulence, low NO_x production, due to effective control of combustion temperature, reliability (no moving parts), flexibility for shock load, adaptability to sludges at different moisture content (dewatered, partially dried, full dried), heat storage capacity by sand bed, and possible abatement of acidic compounds within the bed using additives, like limestone and dolomite.

The FBF can be designed with a hot wind box (400 °C to 700 °C) with distribution plate or air preheating with distribution pipe that reduces the auxiliary fuel consumption in case of wet sludge feeding. Hot wind box means, that the incineration air is warmed up by means of a flue gas pre-heater. Disadvantages include sand carry-over with the ash, and possible formation of a block of vitrified sand when salts with low melting points are present. This problem can be solved by an addition of chemicals to inhibit the binding of certain salts or by filling in fresh sand at a proper time. In the urban sludge treatment, the risk of vitrified block sand is very low.

FBF are usually designed to operate in autothermal conditions (neither use of oil nor natural gas) when applied after drying. FBF is currently recognized as BAT for sludge incineration. There are many existing systems in operation.

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Pressurized fluidized bed furnace is operated under 150 kPaG, then fluidizing air is compressed by using turbo charger installed in the flue gas duct. Additionally, flue gas can be emitted without induced draft fan by its containing pressure. Therefore, this system can decrease electrical power consumption of fans and is considered as energy saving technology (see Annex C).

The capacity of FBF usually ranges up to 6 000 kg DM/h and 40 MW thermal.

FBFs fall into two categories: single (non-circulating) FBF and CFBF. They are based on the same principle, but in the circulating bed unit application of a velocity above the fluidisation one creates very intensive mixing of air and fuel. Particles are carried out of the vertical combustion chamber by the flue gas and are removed in a cyclone to be returned to the FBF through a loop seal. Circulating fluidized bed furnaces are common for firing coal or other high-calorific fuels in power station and have been commercialized for sewage sludge more recently (see Annex C for more information).

A representative schematic diagram of CFBF is presented in Figure 12.

For CFBF, inner diameter is 1,5 m to 2,6 m and height is up to 20 m.

CFB section is composed of a riser that works as a combustion chamber, a hot cyclone that captures circulating particles, a loop seal that prevents back-flowing of unburned gases from the furnace bottom.

Fluidizing sand is blown up from the bottom of the riser by primary air. The velocity of fluidizing sand is 4 m/s to 6 m/s. Part of the sand and unburned char carried out from the top of the riser are captured by the hot cyclone as circulating particles and returned back to the riser through the loop seal. A continuous circulation of fluidizing particles can efficiently transport heat and that achieves uniform temperature (850 °C) distribution in the furnace. In CFBF, sand circulation reduces the pressure loss with respect to FBF.

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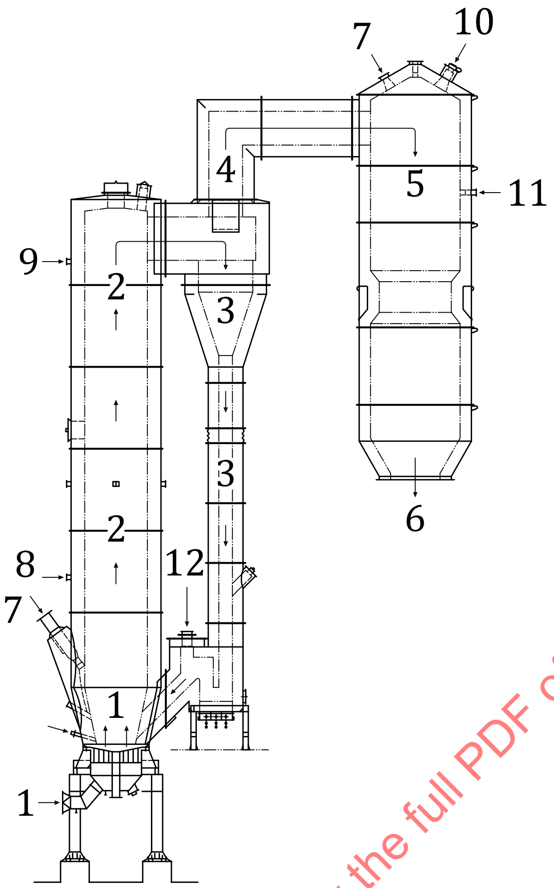

Key

1	fluidizing air inlet	7	burner
2	pyrolysis zone	8	thermocouple
3	circulating sand	9	pressure tap
4	pyrolysis gas	10	sight glass
5	complete combustion zone	11	combustion air
6	exhaust gas and ash	12	sludge inlet

Figure 12 — Circulating fluidized bed furnace

Advantage of advanced two-stage incinerator (CFBs) is N_2O reduction without extra fuel, due to two stage combustion. The operation and furnace are robust against fluctuation in sludge condition and load, due to as the pyrolysis zone is in the CFB (see Annex C for more information).

7.4.2 Multiple hearth furnace (MHF)

A representative schematic diagram of MHF plant is presented in Figure 13. Sludge is fed at the top of the MHF, so-called the “drying zone”, and incinerated in its lowest part, so-called “combustion zone”. Ash is discharged from the bottom hearth. Flue gas is treated using a water scrubber, an alkaline absorber and a wet electrostatic precipitator and then released to a stack thanks to an induced draft fan.

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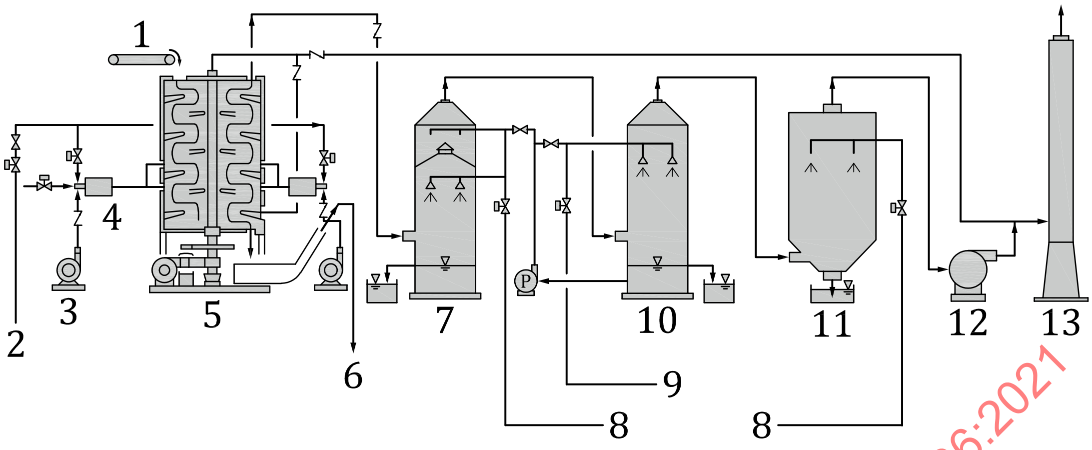

Key

1	sludge	8	treated water
2	fuel	9	NaOH
3	burner fan	10	alkali absorber
4	air heater	11	wet electrostatic precipitator
5	multiple hearth furnace	12	induced draft fan
6	bottom ash	13	Stack
7	water scrubber		

Figure 13 — Typical multiple hearth furnace system

A cross section of a multiple hearth furnace is shown in Figure 14. It consists of a vertical cylindrical-refractory lined reactor containing a number of horizontal hearths. Rabble arms, supported by a single central shaft, rake the sludge radially across the hearths from the top to the bottom, in counter current with air and hot gases.

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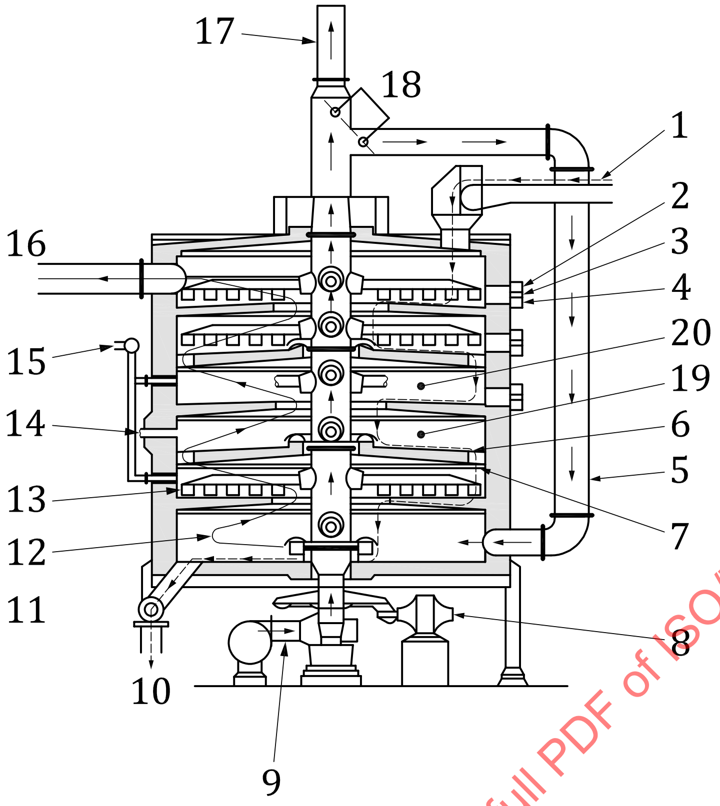

Key

1	sludge cake screenings and grit	11	clinker breaker
2	burners	12	gas flow
3	supplemental fuel	13	rabble arm (2 or 4 per hearth)
4	combustion air	14	auxiliary air ports
5	shaft cooling air return	15	scum
6	solids flow	16	exhaust gas
7	drop holes	17	cooling air discharge
8	rabble arm drive	18	damper
9	shaft cooling air	19	in hearth
10	ash discharge	20	out hearth

Figure 14 — Multiple hearth furnace (typical cross section)

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Three zones can be distinguished in the furnace: drying, with gas temperature up to 400 °C, burning (temperatures of gas and solid phases of 850 °C to 900 °C), ash cooling (temperatures of ashes and air generally lower than 200 °C. Common technical data of a MHF are diameter (2 m to 8 m), number of hearths (4 to 14), hearth loading rate (30 kg to 60 kg wet sludge/m^2.h), excess air (100 % to 125 %).

Advantages are flexibility with respect to feed quality and loading rates, durability, low fuel consumption due to effective heat recovery inside the equipment.

Disadvantages are possible odour problems and emissions of volatile substances, due to the low temperature of exhaust gas, high need of excess air, due to the low turbulence and high maintenance costs, due to many moving parts. Moreover, high fuel consumption is needed, if afterburning of exhaust gases should be accomplished, to take their temperature from 400 °C to 450 °C to at least 850 °C.

The capacity of MHF usually ranges up to 3 000 kg DM/h.

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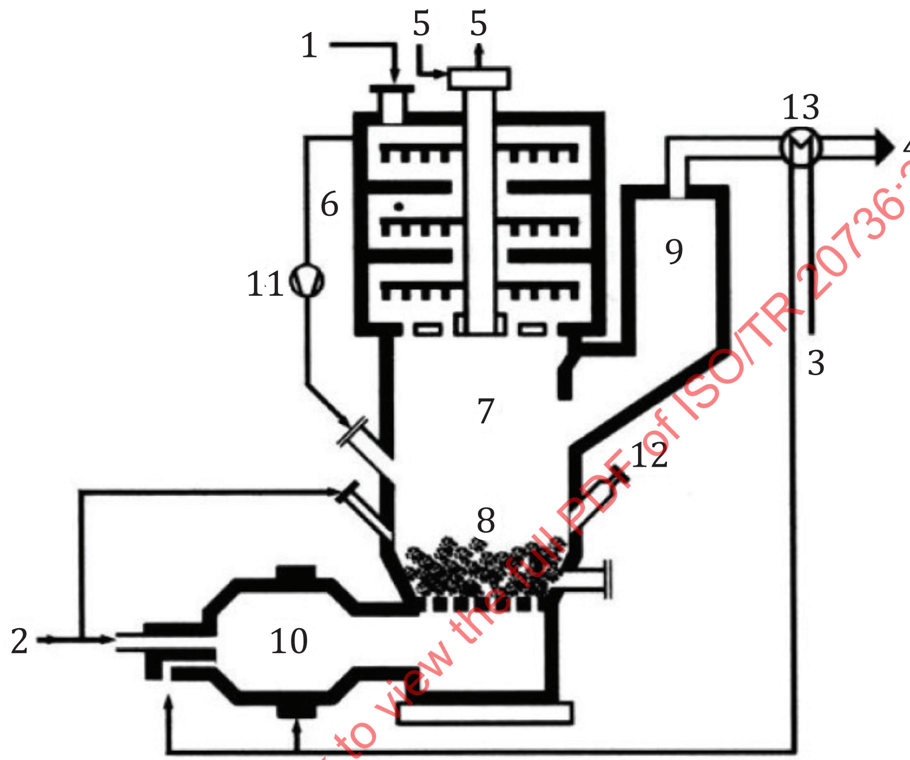
7.4.3 Hybrid furnace

The fluidized bed technology can be combined with the multiple hearth furnace (see Figure 13). In this configuration, the flue gases from the fluidized bed dry the sludge as it moves down through the multiple hearths.

A cross section of a hybrid furnace is shown in Figure 15.



Key

1	sludge supply	8	fluidized bed
2	auxiliary fuel	9	after-burner chamber
3	atmospheric oxygen	10	start-up incineration chamber
4	waste gas	11	circulation blower
5	cool air	12	inspection glass
6	pre-dried zone	13	air preheater
7	incineration zone		

Figure 15 — Hybrid furnace

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Essentially, it consists of a cylindrical brick-faced vertical combustion chamber, in whose lower part a sand bed is kept fluidized with the aid of combustion air. The fluidized bed is operated with hot air from below via the wind box and the tuyeres. The degree of drying of the MHF can be easily regulated, thus improving the overall performance of the process reducing the excess air amount.

As a result of the described process there is an extremely stable, self-sustaining incineration process characterized by low nitrogen oxide and carbon monoxide values in the flue gas. An advantage of this combination is also the possible reduction of the grate surface of the FBF, in comparison with a process where only a FBF is applied. The multi-layer fluidized bed furnace can be operated with an incineration air quantity which is dependent only on the CO and NO_x content of the flue gas and is thus relatively small.

The above conditions can, however, be performed by pre-drying the sludge with different equipment.

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7.4.4 Others

Rotary kiln furnace consists of a refractory-lined cylindrical shell mounted at a slight incline from the horizontal plane (2 % to 4 %) which slowly rotates (lower than 5 r/min). Variation of rotational speed allows to control solids residence time and to ensure adequate mixing. Excess air requirement ranges 50 % to 200 %.

This technology is particularly suitable for incineration of hazardous wastes, due to its ability to treat a great variety of materials of different consistence and size.

Operation involves low combustion efficiency, high need of excess air and high fuel consumption.

The electric furnace (EF) (or radiant heat, or infrared) is basically a conveyor belt system passing through a long rectangular refractory-lined chamber. EFs are available in sizes ranging from 1,2 m wide by 6,1 m long to 2,9 m by 29,3 m. Combustion air flows counter-currently to the sludge. Excess air rates range 30 % to 70 %. No auxiliary fuel is required, because electricity is used to provide supplemental energy.

This technology is particularly suitable for small plants and discontinuous operations.

The cyclonic furnace (CF) is a single hearth unit where the hearth moves and the rabble teeth are stationary. CF introduces combustion air tangential into a cylindrical chamber, while the sludge is sprayed radially toward the heated walls of the chamber: combustion occurs rapidly enough that sludge does not adhere to the walls.

Grate furnace (GF), so-called stoker furnace, consists of step grates, brick wall and ceiling (see Figure 16). Step grates are divided into fixed part and travelling part. These two types of grates are alternately lined and reciprocating movement. Step grates generally consist of drying stage, combustion stage and after burning stage.

Sludge is stocked in hopper and supplied into furnace by feed pusher. It is brought down and carried slowly by grates movement. Incinerated ash is discharged from the bottom of furnace.

Flue gas flow go out from furnace at 850 °C to 1 100 °C. Normally, heat of flue gas is recovered by boiler which is set upper part of the furnace.

Boiler steam is mainly used for drying sludge and generator. Combustion air is supplied from the clearance of grate, and it is also effective for cooling grates.

Advantage is possible to be stably burned high calorific value of sludge, such as dry sludge and low moisture content dewatered sludge, without the use of auxiliary fuel.

Disadvantage is unsuitable for incineration of dewatered sludge of high viscosity with high moisture content.

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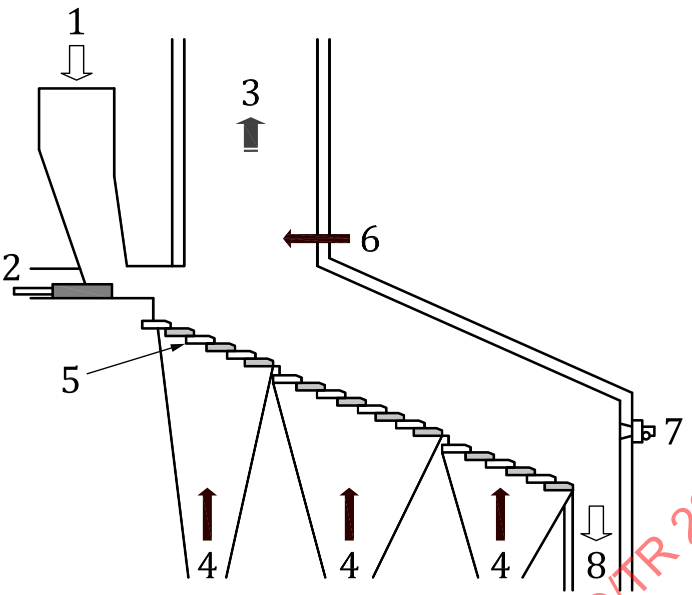

Key

1 sludge inlet
2 feeder
3 flue gas and dust
4 primary air
5 step grate
6 secondary air
7 burner
8 ash

Figure 16 — Grate furnace

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7.5 Pyrolysis

Several types of pyrolysis units are available, including the fluidized bed furnace, the multiple hearth furnace (see Figure 13), and the rotary kiln. These units are similar to incinerators except that they operate at lower temperatures and with less air supply.

Other processes/devices are the Ablative process pyrolyser, the Rotating cone reactors, and the molten-salt oxidation.

In the ablative processes the biomass particles are moved at high speed against a hot metal surface. The process is dependent on surface area and the use of mechanical drivers, making it more complex and more expensive to scale up to larger facilities.

In rotating cone reactors, pre-heated hot sand and biomass particles are introduced into a rotating cone. Like other shallow transported-bed reactors relatively fine particles are required to obtain a good liquid yield.

In molten-salt oxidation, combustible waste is oxidized at 500 °C to 950 °C in a bath of molten salts. There is no direct flame, and this prevents many of the problems associated with incineration.

7.6 Gasification

Commercially available furnaces include fixed bed reactors, entrained bed, fluidized bed, multiple hearth, rotary kiln, and some other patented processes. The basic types have only one stage whereas the more developed ones have two or even three stages. Additionally, there is a process called plasma gasification which is more a gas treatment system than an entire gasification system.

Fixed bed and fluidized bed gasifiers can be considered as dry processes (where the ash does not melt) while entrained flow and plasma gasifiers can be seen as slagging gasifiers (where slag is a vital part to

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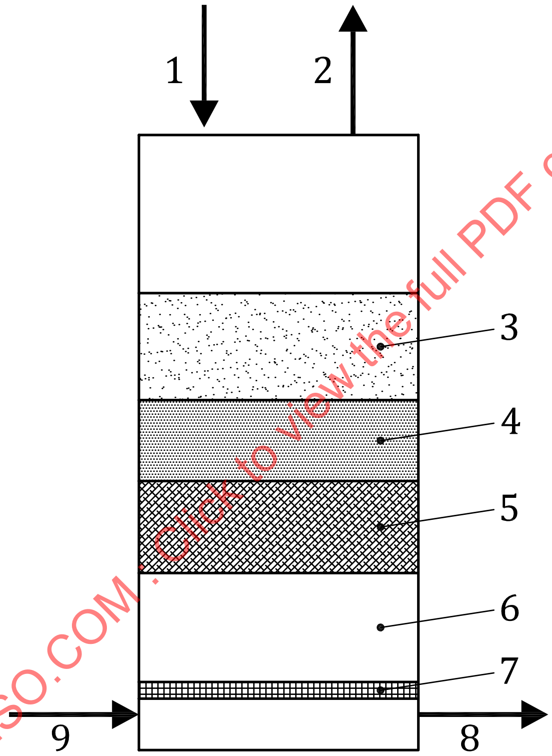
the functioning of the process). The occurrence of the slag depends on local temperatures and the so-called ash melting point.

Looking to the applications, a further distinction can be made between power gasifiers and heat gasifiers. Power gasifiers require a more or less tar- and dust-free gas, while heat gasifiers are not very sensitive to these types of impurities.

— Fixed bed gasifiers: have a stationary reaction zone typically supported by a grate and operate at low temperatures (400 °C to 650 °C) for the outlet gas and have high thermal efficiency. Small-scale gasifiers are generally of this type. Up-draught or counter-current gasifier (see Figure 17), is the oldest and simplest type of gasifier. The air intake is at the bottom and the gas leaves at the top. The tars and volatiles produced during this process are carried in the gas stream. Ashes are removed from the bottom of the gasifier. In the down-draught gasifiers primary gasification air is introduced at or above the oxidation zone in the gasifier. The producer gas is removed at the bottom of the device, so that fuel and gas move in the same direction, as shown in Figure 18. Downdraught gasifiers have the potential of producing a tar-free gas suitable for engine applications.



Key

1	feedstock	6	hearth zone
2	gas	7	grate
3	drying zone	8	ash
4	distillation zone	9	air
5	reduction zone		

Figure 17 — Up-draught or counter-current gasifier (typical cross section)

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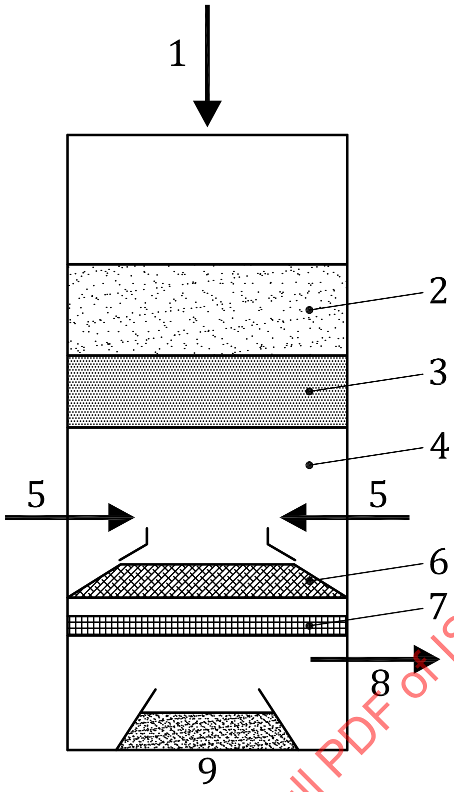

Key

1	feedstock	6	reduction zone
2	drying zone	7	grate
3	distillation zone	8	gas
4	hearth zone	9	ash pit
5	air		

Figure 18 — Down-draught or co-current gasifier

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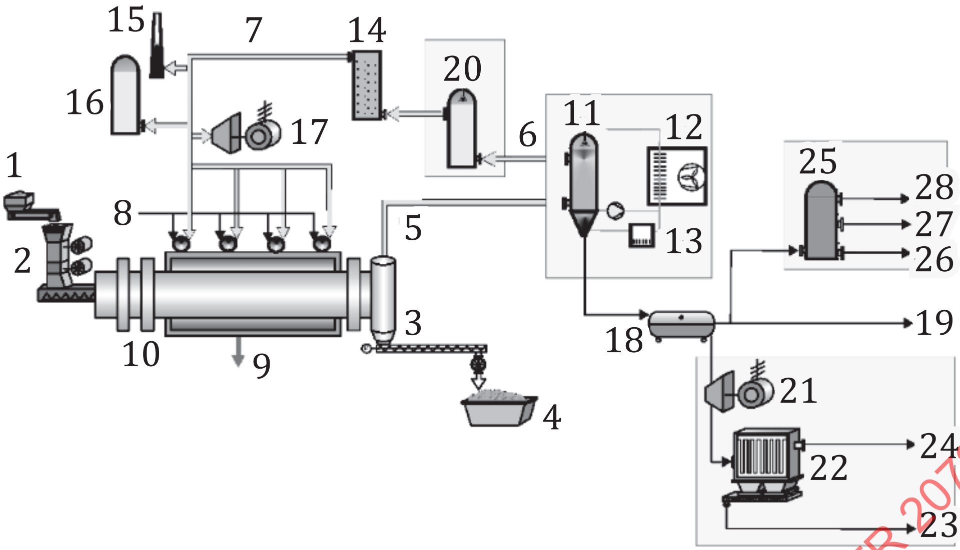
— In the entrained flow gasifiers, the feedstock (fuel) is suspended by the movement of gas to move it through the gasifier. Finely pulverized fuel (100 µm to 600 µm) is gasified within seconds at high temperatures (1 500 °C to 1 900 °C). The feed is entrained with oxygen and steam in a co-current flow, which requires an air separation unit which increases costs and energy use. The gasification process quick reaction time allows for a very high throughput, less problem with caking fuels, and highly efficient carbon conversion. Due to the high temperature of the outlet gas (1 250 °C to 1 600 °C), the product gas contains no tar or methane, but requires a large effort in gas cooling.

In fluidized-bed gasifiers the turbulent mixing results in uniformity of the product gas and gives a maximum heat and mass transfer between the gases and solids. It also results in a high throughput, although not quite the level of entrained flow gasifiers. Operating temperatures are around 500 °C to 1 000 °C depending on heating methods, indirect heating being the lower. Depending on design, biomass can be fed into the top, bottom, or middle of the fluidized bed. Heat to drive the gasification reaction can be provided in a variety of ways in fluidized bed gasifiers.

A commercial gasification treatment plant on a basis of fluidized bed technology is described in Annex C.

7.7 Thermolysis

Thermolysis mostly involves a twin casing, rotating drum type reactor; the heat is injected exclusively through this twin casing. A flow diagram of thermolysis is presented in Figure 19.



Key

1	hopper	15	emergency flare
2	input sluice	16	gasometer
3	thermolysis-coke hot	17	CHP
4	thermolysis-coke cold	18	raw oil tank
5	thermolysis raw gas	19	thermolysis oil, raw
6	permanent gas	20	desulfuring
7	permanent gas, cleaned	21	oil-CHP
8	GPL / natural gas	22	off-gas filter
9	off gas	23	filter dust
10	rotary kiln unit	24	off-gas
11	condensation	25	distillation
12	cooler	26	super fraction
13	filter	27	light oil fraction
14	activated carbon filter	28	heavy oil fraction

Figure 19 — Flow diagram of thermolysis with usual rotary kiln unit

7.8 Carbonization

Several types of carbonization units are available, as referred to in 7.5, including FBF, multiple hearth furnace (MHF), rotary kiln furnace and so on. A case study is presented in D.3. The rotary kiln furnace is used in many cases including large scale projects, while FBFs have many references as well. Some good references are incorporated in the case study in this guideline.

Generally, the drying process is required prior to the carbonization process. Bio-charcoal generated from the process could be pelletized, depending on its application. Syngas (or pyrolysis gas) is combusted in a post-combustion process with enough high temperature and residence (or residence) time and the acidic substances in the flue gas are removed in a scrubbing process after a dust-collector. The excess heat recovered from the post-combustion process is reused for drying and carbonization processes.

7.9 Wet oxidation

Commercial systems typically use a bubble column reactor, where air or pure oxygen is bubbled through a vertical column that is full of the hot and pressurized fluid to be treated. Fresh fluid (wastewater or

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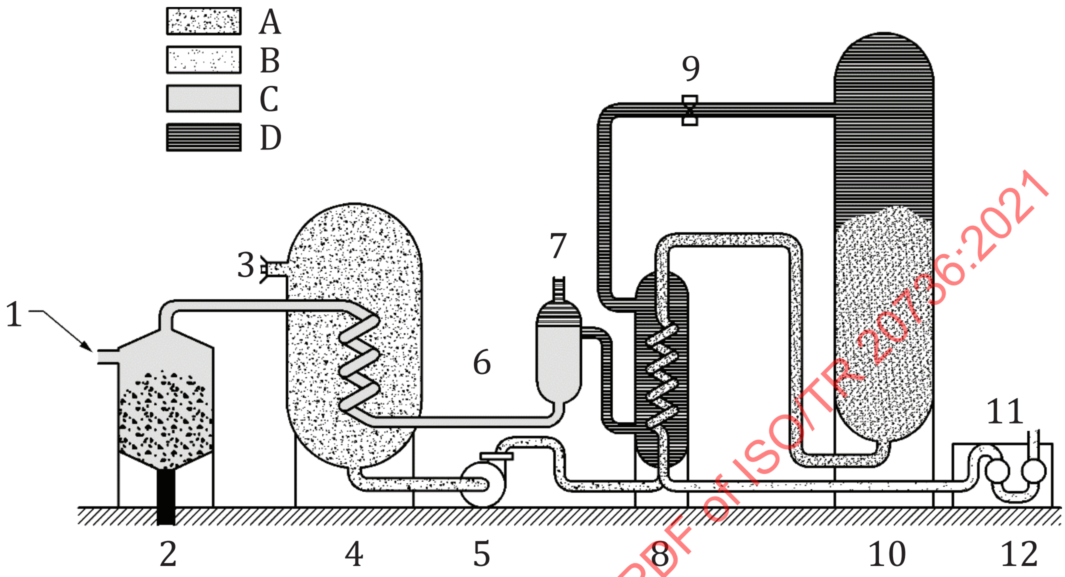
sludge) enters the bottom of the column and oxidized fluid wastewater exits the top. The heat released during the oxidation is used to maintain the operating temperature, together with the use of heat exchangers. Other systems use fully/perfectly mixed reactor.

A diagram is presented in Figure 20.



Key

A	sludge	5	sludge pump
B	air	6	separator
C	effluent	7	steam and flue gas outlet
D	gases	8	heat exchanger
1	effluent outlet	9	pressure relief valve
2	ash outlet	10	reactor
3	sludge inlet	11	air inlet
4	holding tank	12	compressor

Figure 20 — Schematic diagram of wet oxidation sludge

7.10 Melting

Melting is not frequently used in Europe and has been used in Japan.

A representative schematic diagram of a vortex melting system is shown in Figure 21 and a diagram of vortex melting furnace is shown in Figure 22.

Sludge is dried and then fed into the melting furnace. Melting slag is discharged from the melting furnace to slag cooler. The heat of flue gas is recovered and utilized for combustion air heating and dryer heat transfer medium (air or steam) heating as heat source. The flue gas treatment process for melting system is almost the same as that of FBF.

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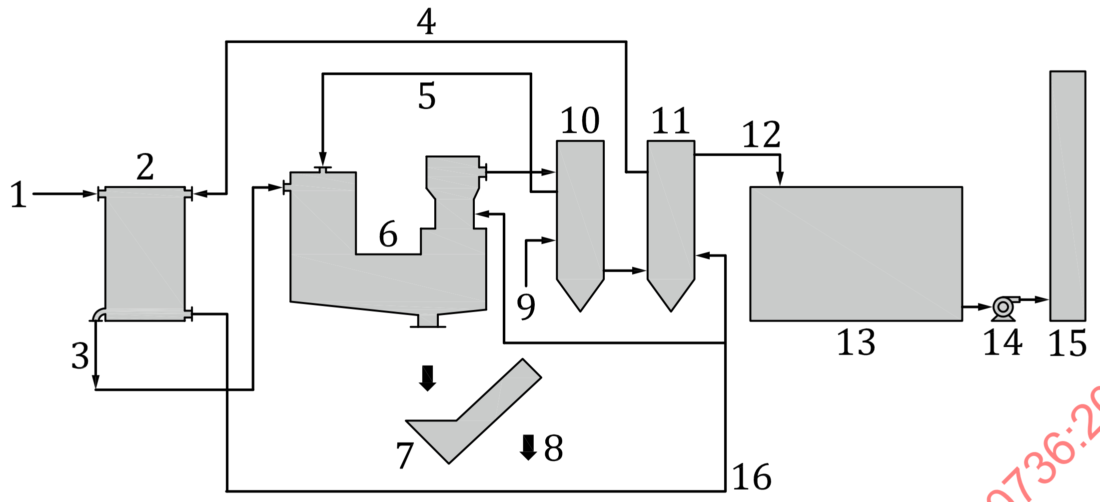

Key

1	sludge	9	air
2	dryer	10	air heater
3	dried sludge	11	evaporate heater
4	hot evaporate	12	flue gas
5	combustion air	13	flue gas treatment
6	melting furnace	14	induced draft fan
7	slag cooler	15	stack
8	slag	16	evaporate

Figure 21 — Typical vortex melting system

There are vortex melting, surface melting, coke bed melting and rotary kiln as typical melting furnace. There is electrical melting furnace but this type of furnace is not popular for sewage sludge melting.

In case of dewatered sludge melting, sludge is pre-dried to optimize fuel usage in order to maintain the temperature above the melting point of the inorganic part of sludge. The melting point is ranging from 1 100 °C to 1 250 °C. Because melting furnace is operated under higher temperature than incineration, too much excess combustion air at the high temperature zone makes nitrogen in the air oxidized then nitrogen oxide (NO_x) is easily formed. Therefore, at the high temperature zone, combustion air is limitedly supplied to prevent nitrogen oxide formation, then at under 1 000 °C zone unburned substances is completely combusted with enough oxygen which is called two stage combustion and might be applied for sludge melting. Considering flue gas emission regulation, flue gas de-NO_x such as SCR might be applied if necessary.

Similar to incineration, flue gas heat is recovered as combustion air preheating source and/or dryer heat source, incinerated ash is collected and toxic material in the flue gas is treated. A part of metals in the sludge, which is low boiling point metals, are evaporated in the furnace then induced with flue gas. Such metals are cooled and solidified again at the stage of heat recovery and flue gas treatment, then discharged as melting fly ash. Because the melting fly ash contains heavy metals, the fly ash is disposed after heavy metal leach out prevention treatment to prevent secondary pollution at the final disposal area.

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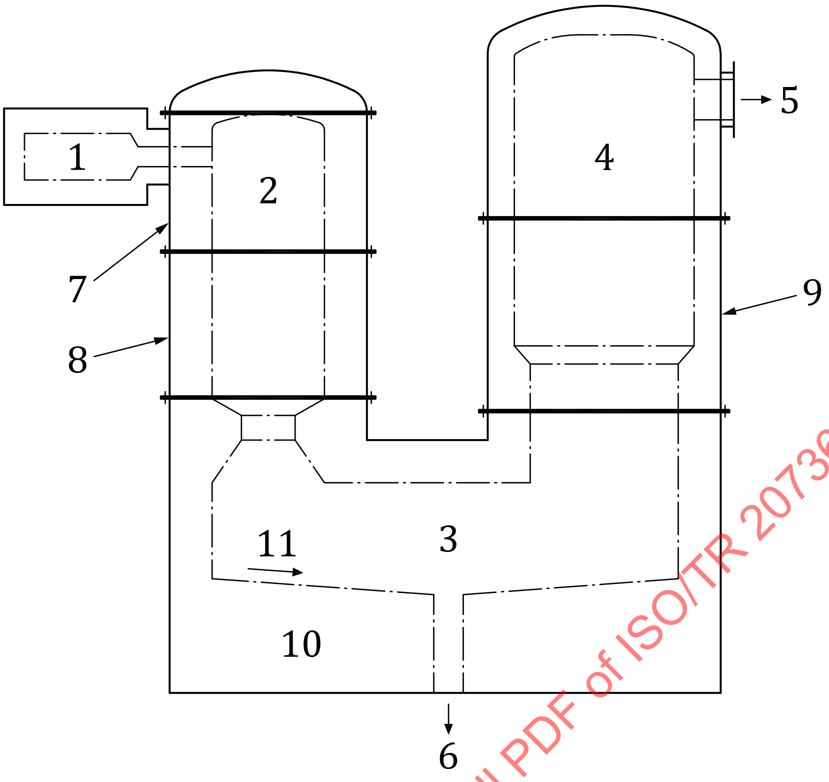

Key

1	air heater	7	sludge inlet
2	vortex melting zone	8	primary inlet
3	slag separation zone	9	secondary air inlet
4	secondary combustion chamber	10	refractory
5	flue gas outlet	11	slag flow
6	slag port		

Figure 22 — Vortex melting furnace

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7.11 Pasteurization

Sludge pasteurization is usually carried out under low temperature up to 70 °C for about 30 min. Two methods exist for such purpose: the first one consists in applying steam by means of direct injection and the other one involves indirect heat exchange. Direct steam injection seems to be a more feasible approach as use of heat exchangers often leads to scaling, fouling and especially clogging caused by build-up of organic matter over time. Steam injection is moreover preferred because heat transfer through the sludge slurry is slow and not dependable. A typical sludge pasteurization system using the direct steam injection approach usually involves feeding a preheated sludge going up to 55 °C and then mixed with incoming steam before diverting it to reactors and maintained for specific time period. In order to ensure efficient heat transfer so that operating cost can further be lowered, in-line mixing should be incorporated into the design which also helps to maintain a uniform heating. Incomplete mixing either increases heating time, reduces process effectiveness, or both. Overheating or extra detention times are not desirable, however, because trace metal mobilization may be increased, odour problems are exacerbated, and unneeded energy is expended. Batch processing can be preferable to avoid reinoculations if short circuiting occurs.

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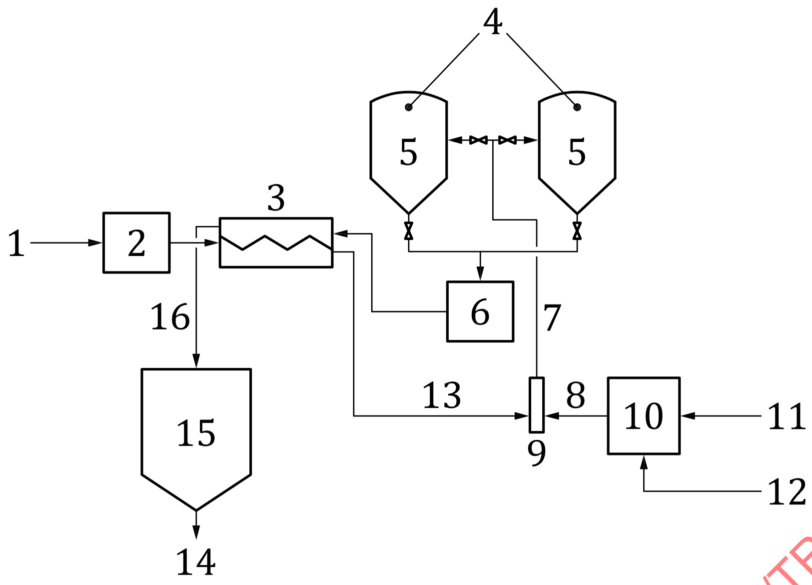

Key

1	untreated or digested sludge from storage	9	in-line mixer
2	raw sludge feed pumps	10	boiler
3	heat exchanger	11	fuel
4	pasteurization reactions	12	make up water
5	157 °F (70 °C)	13	pre heated sludge 135 °F (57 °C)
6	pasteurized sludge pumps	14	sludge for utilization
7	heated sludge 157 °F (70 °C)	15	pasteurized sludge storage
8	steam 345 °F (174 °C)	16	pasteurized sludge

Figure 23 — Typical pasteurization system

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The flow scheme for a sludge pasteurization system also includes heat recuperation system. System components include a steam boiler, a preheater, a sludge heater, a high-temperature holding tank, blow-off tanks, and storage basins for the untreated and treated sludge (see Figure 23).

Pasteurization is employed extensively in Western Europe, where heat pasteurization is a proven technology, requiring skills such as boiler operation and understanding of high-temperature and pressure processes. Pasteurization can be applied to either untreated or digested sludge with little pretreatment.

7.12 Emerging technologies

7.12.1 General

Emerging technologies relates to technologies studied at pilot scale but with few full-scale applications.

7.12.2 Oxidation technologies

7.12.2.1 Supercritical water

Supercritical water treatment, also called hydrothermal treatment is based on the property of water above 374, 20 °C and 22,1 MPa to reach a super critical instability that is similar to a condition of vapour and liquid in one plasma like fluid. The characteristics of solutes in water and reaction kinetics completely change in the hydrothermal range. Treatment of sludge in supercritical water can be performed according to three methods: supercritical water gasification (SCWG), supercritical water

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partial oxidation (SCWPO) and supercritical water oxidation (SCWO) technologies with increasing amounts of oxidants. Hydrogen-rich gases can be generated from by SCWG or SCWPO technologies using oxidants less than stoichiometric ratio while organic compounds can be completely degraded by SCWO technology using an oxidant excess. The addition of an oxidant secures immediate and complete oxidation with the formation of high-quality effluents, capture of CO_2 through formation of carbonate salts, formation of inert ashes and release of air emissions. The different process variables are sludge properties, moisture content, temperature, oxidant (peroxide, oxygen) amount and catalysts. Few commercial plants were built. Corrosion or plugging problems, especially during the preheating of sludge, restrict this technology. Therefore, decomposition of organics with hydrothermal flames using auxiliary fuel instead of preheating may be an alternative.

7.12.2.2 Wet peroxide oxidation

Wet peroxide oxidation (WPO) constitutes an alternative to the basic WAO technology by using hydrogen peroxide in addition to oxygen as oxidant, possibly associated to a catalyst. This process is adapted from the classical Fenton's reaction but operates at a temperature of about 120 °C. This process originates from the wastewater treatment field.

7.12.3 Enzymatic sludge hydrolysis

Low temperature (<100 °C) thermal pretreatment enhances sludge floc hydrolysis by enzymatic activity. In Japan, some full-scale operating plants exist.

7.12.4 Plasma gasification

Plasma gasification is a non-incineration thermal process that uses extremely high temperatures in an oxygen starved environment to decompose input waste material completely into very simple molecules. The main product of the process is a gas, known as synthesis gas, which can be used, among others, for the production of energy and an inert vitreous by product material, known as slag. The plasma furnace is the central component of the system where the gasification process takes place. Two graphite electrodes, as a part of two transferred arc torches, extend into the plasma furnace. An electric current is passed through the electrodes, and an electric arc is generated between the tips of the electrodes and the conducting receiver, i.e. the slag in the furnace bottom. The gas introduced between the electrode and the slag that becomes plasma is commonly air. At the temperatures maintained within the plasma furnace, the organic molecules contained in the sewage sludge begin to break down and react with the air to form carbon monoxide, hydrogen and carbon dioxide. Water contained in the sludge feed also dissociates and reacts with other organic molecules. As a result of these reactions, all organic constituents and water are transformed into a synthesis gas containing mostly hydrogen, carbon monoxide and nitrogen.

7.12.5 Ultrasound pretreatment

Ultrasound irradiation is regarded as a rapid pretreatment method used to dissociate the biomass of the sludge, simple to operate. The high-power ultrasound pretreatment induces a rise in the temperature of the system, which further increases the efficiency of sludge disintegration. The organics released can then easily be hydrolysed. There are ultrasound pre-treatment systems installed in treatment plants around the world.

7.12.6 Microwave irradiation

In the electromagnetic spectrum, microwave (MW) irradiation occurs in wavelengths of 1 m to 1 mm at corresponding frequencies of 300 MHz (3×10^8 cycles/s) to 300 GHz (3×10^{11} cycles/s), respectively. The mechanism of MW irradiation includes a thermal effect and a thermal effect. In recent years, many investigations were devoted to MW irradiation as an effective thermal method for sludge treatment, mainly due to its rapid and selective heating, energy efficiency, capacity to enhance the yield and quality of product and diminished hazardous product formation and emissions. System design and development inhibit the wider application of MW technology to industrial processes. Most of the work undertaken in this field has been restricted to the laboratory.

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7.12.7 Infrared radiation

Infrared radiation (IR) is defined as the electromagnetic radiation with a wavelength comprised between 0,8 µm and 1 000 µm. It has the property to transmit heat, so it can be used as a heating source during drying. Compared to conventional convective drying systems, the heat transfer during IR drying can be more efficient, leading to shorter processing time, lower energy costs and more compact equipment.

7.13 Design aspects

General indications on design aspects of different thermal treatment devices are difficult to be given because a lot of different systems are available on the market, each generally covered by patents or specific trademarks.

Main factors to be taken into consideration in sizing a thermal treatment device include:

— the amount of sludge;

— the specific amount of water to be evaporated (in relation to DM content);

— the calorific value.

In the case of combustion, above three parameters allow the determination of a nominal operating point expressed as the thermal capacity of the furnace and with respect to which various operating zones are determined. These different zones are represented in an operating diagram called a combustion chart[20].

It is recommended that a chart is used prior to carrying out any sludge/waste combined incineration, irrespective of the envisaged furnace type, the composition of the sludge and waste to be supplied.

It is also to be considered that anaerobic digestion reduces organic content of sludge, and therefore its calorific value, but also produces biogas which can be a source of energy for the thermal treatment process. Further organic compounds containing organic sulfur are degraded by anaerobic digestion and together with organic compounds are reduced to ammonia nitrogen and sulphide sulfur. Such forms of N and S are easily released from sludge into sludge liquor (N) and into biogas (S) thus reducing the amount of such compounds in the flue gas.

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7.14 Auxiliary equipment

7.14.1 General

The performance of thermal processes is dependent upon the provision of auxiliary equipment which may include:

— upstream treatment units;

— transport, receiving area, storage and feeding systems;

— heat supply and recovery;

— compressed air system;

— flue gas/ waste gas cleaning;

— ash and other residues handling;

— wastewater (coming from gas cleaning and sludge drying) treatment and return;

— process and analytical instrumentations and control systems;

— safety systems.

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7.14.2 Transport, receiving area, storage and feeding systems

Treated sludge can be transported by barge, rail truck, road or pipeline. The most suitable method depends on the dry solid content of the sludge and transport duration and length. Transport by trucks is the most widespread method due to its relatively low investment costs and the high degree of flexibility.

The receiving area includes unloading equipment and storage vessels. DM content and physical consistency of the sludge influence their selection and design.

To avoid emission of malodorous, sludge should be stored in closed systems from which air is extracted and treated. Attention should be paid to the explosive and fire risks related to handling sludge and carbonized materials. It can be advantageous to store sludge on the thermal treatment plant site, because this provides a buffer between the sludge production and its treatment.

Particular attention should be paid to appropriate planning of maintenance operations.

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7.14.3 Heat supply and recovery

7.14.3.1 General

The systems for heat recovery include boilers, with production of hot water or steam, and heat exchangers used for air heating and/or flue gas after-heating, heat exchanger on thermal oil heating.

7.14.3.2 Heat exchangers

Several types of exchangers are used and involved in several thermal processes for sludge treatment. The major concerns in applying a heat exchanger on dirty or sticky media like sludge are

— fouling and plugging of the tubes or plates due the solid accretion;

— abrasion by the entrained solids;

— corrosion due to vapours.

A particular attention should be drawn to the design and material composition of heat exchange surfaces and the provision of cleaning systems.

7.14.3.3 Boiler

The boiler can be provided with a dust hopper fitted with a screw conveyor for removing dust that settles out.

Soot blowers are required for cleaning the tubes. Due to structure of the fire tube boilers, with many long tubes of relatively small diameter connected to a tube sheet, soot blowers might not be effective in eliminating deposits from the inside of the tubes. The use of high gas velocity could limit build-up of solids.

In combination with drying process as a pre-treatment, the exhaust gases enter the boiler at 850 °C to 950 °C in the radiant section, then pass through the convective section and leave the boiler from the economizer. Exit flue gas temperature from economizer can be as low as 250 °C when electrical energy is recovered. Corrosion should be controlled taking into consideration acid dew point in relation to this flue gas temperature. It can be also as high as 500 °C when steam is produced. However, the temperature of the exhaust gases into the boiler can be changed in different process configuration such as direct dewatered sludge incineration.

Steam production from the boiler can be estimated in the range of 3 kg/kg to 8 kg/kg dry solids to be processed. Electric energy conversion can be estimated in the range 0,2 kWh/kg to 1,6 kWh/kg dry solids depending on process configuration. The use of an induced draft fan after the scrubber is desirable with a waste heat boiler installation to prevent gas and dust leakage. If the steam demand

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is highly variable, the use of a hot gas by-pass duct to the scrubber inlet is advisable; otherwise, a condenser is required.

The use of produced steam depends on local conditions and plant size.

Steam can be used for electricity generation by conventional turbines, sludge drying in indirect contact steam-sludge devices, air preheating in finned exchangers, exhaust gas post-heating to prevent the plume appearance and to ensure sufficient dispersion of the effluent gases, and district heating or industrial use.

7.14.4 Gas cleaning

Air pollution control is required for the reduction of emissions which include particulate, volatile trace elements, organic pollutants (volatile and products of incomplete combustion or drying), acidic compounds, nitrogen and sulphuric oxides. The main goal of any flue gas cleaning system is to cool down the exhaust gas thus condensing most of the evaporated pollutants.

More details of equipment for gaseous emissions cleaning are reported in Clause 9.

7.14.5 Ash and other residues handling

The solid residues of sludge combustion are generally classified as bottom (if they are taken directly from the furnace) or fly ashes (if they are collected in the flue gas treatment devices). In sludge treatment by MHF bottom ashes are generally prevalent, while in FBF incineration fly ashes are much more abundant. Larger particles such as sand can be evacuated directly from the sand bed using an evacuation valve placed at the base of the sand bed.

In some FBF installations, however, discharging of heavy materials from the bed is also considered when the head losses in the bed reach unsuitable values does requiring the replacement of sand.

More details of equipment for solid residues treatment are reported in Clause 9.

7.14.6 Wastewater treatment

Wastewater is originated from wet scrubbers or condensation systems. It can contain pollutants, like trace elements, acidic compounds, odorous compounds and solids at levels that require treatment to meet effluent standards for discharge. Chemical-physical processes like neutralization, oxidation, trace elements precipitation, suspended solids removal can be used.

More details on wastewater treatment are reported in Clause 10.

7.14.7 Process monitoring

To maintain steady-state conditions and to guarantee high process efficiency, key operating parameters like temperature, pressure and oxygen concentrations should be properly controlled and continuously measured in the thermal system (e.g. furnace) and in different sections of the full treatment plant.

In addition, the measurement of other operating parameters like the gas flow rate at the stack exit can indirectly give information on residence time and turbulence in the system.

A periodic monitoring of toxic metals of sludge should be carried out to ascertain the standard limits are respected. Control of trace elements and some organic micropollutants should be also accomplished.

In all cases, it is particularly important to determine the ranges within which change is acceptable and/or unacceptable for parameters of interest. Among all of these parameters, a selection of those, which should be regularly monitored and/or inspected, should be proposed.

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7.14.8 Safety systems

Sludge thermal treatment units should be subject to appropriate safety measures because they can represent many risks, particularly in the event of malfunctions; The following risks should be particularly managed: risks due to the self-heating properties of dried sludge, risks associated to the gas emissions like pyrolysis gases, risks of explosions, risks of sparkling phenomena.

According to these considerations, each plant needs to undergo a hazard and risk analysis.

Usual related safety systems include explosion-proof, water shower for chemical exposure, thermal insulation, firefighting. Safety parameters should be included in the functional analysis of the system and should be part of its automation.

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8 Operational aspects

8.1 General

Thermal treatment processes should be operated continuously as this leads to a minimum of energy consumption and wear costs.

Thermal processes generally require appropriate preliminary treatments to improve the treatment quality of sludge. Thickening, conditioning and dewatering are the most common processes for reducing moisture. Anaerobic digestion also plays an important role.

Inorganic conditioners determine a decrease in volatile content (reduction in sludge heat content) and an increase in dry solids quantity (increase of ash amount) to be processed. Further, slagging and clinkering can occur when metal salts are present, while chlorine and other halogens are responsible for the presence in the exhaust gases of acidic compounds which are undesirable for corrosion problems involved, especially at high temperatures. The use of polymers as dewatering aids is very effective, and their adoption instead of lime and ferric chloride when the sludge is to be incinerated.

Addition of lime to slow down sludge fermentation may have a positive impact on transport and storage, but the life cycle of the refractories can be reduced due to alkaline degradation at these temperature levels, and additional clogging occur in the furnace's boiler unit.

The advantages of thermal drying when coupled with incineration consist of the possibility to control the solids concentration to the right value, which allows an autothermal combustion with a minimum exhaust gas production to be obtained.

Dried and dewatered sludge can be mixed, if necessary, to avoid DM concentrations higher than needed.

Addition of a supplemental combustible material at low cost, like appropriate biomass, is another option to reduce fuel consumption.

Operating and safety problems can arise from addition of scum and grease because, due to their high energy content, an increased volume of exhaust gases is suddenly produced in the heating space.

Induced draft fans should be able to draw off the developed explosive gas immediately to prevent any escape in the ambient air.

Thermal processing plants should be inspected and cleaned on a regular basis to detect the presence of slagging and clinker deposits, preventing natural circulation of air, and of cracked refractory with possible loss of material. The burner operation without impingement of any surface should be warranted.

Anaerobic digestion reduces organic content of sludge, and therefore its calorific value, but also produces biogas which can be a source of energy for the thermal treatment process. Further organic compounds containing organic sulfur are degraded by anaerobic digestion and together with organic compounds are reduced to ammonia nitrogen and sulphide sulfur. Such forms of N and S are easily released from

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sludge into sludge liquor (N) and into biogas (S) thus reducing the amount of such compounds in the flue gas.

In the following subclauses, specific aspects of thermal processes are discussed.

8.2 Drying

Drying of the sludge follows mechanical dewatering. Principal arguments for implementing drying are: a further reduction of the sludge amount to be handled, a further increase of the calorific value, a further stabilization and increased hygienic safety, an improved storage and transportability, an elimination of the problems with handling paste-like substances.

Some technologies are inappropriate when a high viscosity phase occurs during the sludge drying. In this case, recirculation of dried sludge is commonly used so that the feed is above the critical dry solids content level, close to 60 %.

Thermal drying can be required to allow auto-thermal incineration in monovalent sewage sludge incineration plants depending on the composition of the sludge (energy content of the dry solids, largely related to the content of organic material). Pre-drying should only be carried out up to the point at which the sludge contributes positively to the energy balance of the following incineration process. Dried sewage sludge represents a free-flowing granulate with low to medium calorific value which can be used as added fuel especially in power plants and cement kilns.

8.3 Hydrolysis

Thermal hydrolysis of waste activated sludge is a robust pretreatment, leading to significant improvements in anaerobic digestion (up to 70 % increases in methane production) operating in quite a wide range of experimental conditions. The key mechanisms and variables of the process are: heating (temperature and time) and decompression mechanism (slow or steam explosion). The efficiency of the pretreatment is mainly influenced by temperature.

In the coupling of thermal hydrolysis with downstream digestion, the energy balance is relatively neutral as additional biogas produced during digestion is partly counteracted by the energy requirements to provide reaction temperature for treatment.

In the coupling with other downstream thermal technology, improvement in sludge dewaterability reduces downstream transport and sludge handling, especially for drying.

8.4 Incineration

8.4.1 General

Generally. the primary variables affecting incineration performance and costs are the waste calorific value, the fuel consumption and in some cases the air requirement.

An autothermal combustion is obtained when the calorific value of sludge and the heat content of combustion air, if preheated, balances the heat content of exhaust gases and the heat losses at the combustion temperature.

Fuel requirement strictly depends on DM and excess air needed to ensure a complete combustion. Generally, fuel requirement lower than 70 m^3 of methane (measured under normal conditions of temperature and pressure) per wet ton of sludge is considered suitable for an incineration process.

The stoichiometric quantity of air (in kg) is 4,31 times that of oxygen. Depending on incinerator type, 3 % to 6 % O_2 residue in the flue gas is generally required to ensure effective operation.

The temperature is controlled by acting on the fuel, if sludge is not autothermal or by feeding surplus air or by injecting water in the opposite case.

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Typical operational problems of incineration systems can include corrosion, metal fatigue, slagging and blocking of feeding systems.

Maintenance operations should be carried out with regard to the burners, the firebricks, the exhaust gas duct (especially the elbows), all the moving mechanical elements, and the exhaust gas cleaning system.

Different procedures for start-up and shut-down should be adopted depending on furnace type. In any case, the refractory drying before the first start-up is one of the most delicate and important operations to be carried out.

Specific operational aspects for the most used furnace types are discussed in the following subclauses.

8.4.2 Fluidized bed furnace

Stationary fluidized bed incineration plants make up about 90 % of the capacity of municipal mono-incineration plants. For about 30 years, stationary fluidized bed furnaces as well as multiple hearth furnaces have proven to be very well suited for incinerating sewage sludge, a fuel with very specific characteristics.

One of the advantages of the FBF is the ability to operate with a higher flexibility than other systems. It is very responsive to variations in feed quality and rate. The sand bed acts as a heat reservoir thus reducing the temperature drop when the furnace is temporarily out of service.

However, the FBF is limited by fluidizing air requirements, which means the unit should operate near design loading even for short periods.

Mechanically dewatered sludge can be incinerated in fluidized bed furnaces after preliminary partial drying or in combination with pre-heating of combustion air to > 500 °C. Sludge incineration is typically combined with drying as pre-treatment, however other combinations exist. Preliminary drying for autothermal combustion is not necessary, if the heating value of the sludge is increased to 4 000 kJ/kg – 4 500 kJ/kg by adding coal or other high-calorific substances. However, detailed engineering calculation is required for actual achievement of autothermal combustion.

A very even distribution of the sludge over the entire furnace cross section is achieved by using bulk fuel spreaders. When expanded, the hot fluidized bed offers ideal conditions for mass and heat transfer.

If, in addition to sludge, also screenings are to be incinerated, these should be comminuted and bulk materials should be removed beforehand.

The air is fed in the wind-box or thanks to a distribution pipe to ensure a proper air distribution below the orifice plate. Fluidizing air is passed through this plate by nozzles and fluidizes the sand bed. The depth of the static bed is usually 0,5 m to 1 m. During fluidization this depth approximately doubles and therefore reaches 1 m to 2 m.

The pressure drop of the bed ranges from 7,5 kPa to 28 kPa. The total pressure drop strictly depends on nozzle design and the quantity and bulk density of sand. Quartz sand has a bulk density of approximately 1 500 kg/m^3. The sand particle size ranges 0,4 mm to 2,0 mm depending on the fluidisation rate. The particle size in the bed determines the maximum span that prevents transport of the bed out of the reactor.

The fluidized bed sand is subject to abrasion, which means that very fine dust-like sand particles are discharged with the ash in the flue gas. Normally, the removed amount of sand is replaced by the sand contained in the incinerated sludge. If the sludge does not supply sufficient sand quantities, then extra sand should be added. If the amount of sand in the fluidized bed increases above a certain permitted level, it should be reduced to the permitted amount using a special fluid bed ash discharge system. This process is controlled by measuring pressure drop in the fluidized bed.

Fluidized bed furnaces are equipped with injection lances, which can be used to add auxiliary fuels such as oil or gas directly to the fluidized bed, in order to raise combustion temperature. These lances can also be used to inject water, if temperatures are too high and the fluidized bed needs to be

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cooled. Next to a preheat burner for start-up, fluidized bed furnaces are normally also equipped with a freeboard burner. During the start-up phase, the freeboard burner is used to ensure that combustion temperatures are raised above 850 °C as required by emission rules.

The temperature of the bed is generally maintained at 650 °C to 820 °C. For controlling the combustion temperature without auxiliary fuels, either steam or flue gas pre-heaters are used. Above the fluidized bed incineration of CO and combustible dust takes place and the temperature increases to 850 °C to 950 °C in the freeboard. The combustion gases, with the entrapped ashes, exit with freeboard temperature. The combustion zone above the fluidized bed should be large enough to allow the complete burnout of all combustible material. According to emission rules, a minimum gas residence time of 2 s > 850 °C is required. Remaining fly ash is discharged from the furnace with the flue gas. Flue gases are then passed to the heat recovery system, the dust separation step and further flue gas purification processes.

In order to keep carbon monoxide and nitrogen monoxide formation as low as possible, fluidized bed furnaces could be equipped with a staged air supply system. Therefore, the fluidized bed furnace is operated at sub-stoichiometric combustion, which produces a minimal NO_X-fraction and an increased carbon monoxide fraction. The carbon monoxide is then incinerated in the afterburner chamber by adding secondary air. This type of staged combustion enables to keep the limit values for NO_X and CO stated in emission rules without requiring additional NO_X removal measures.

Fluidized bed furnaces for sludge incineration have been designed for combustion capacities up to 6 000 kg/h DM and 40 MW thermal.

The advantages of CFBF only become apparent for combustion heat capacities above 50 MW and for fuels with higher heating values.

8.4.3 Multiple hearth furnace

Autothermal combustion can be accomplished with DM of about 25 % to 30 %, because in this system a drying process is integrated.

Sludge feeding rate should be as much constant as possible to avoid flame extinction and migration of the combustion zone upward (in the case of a surplus heat in feeding sludge) or downward (increase of the moisture content).

Good operating mode implies that combustion zone should be kept in the lower part of the furnace.

Problems encountered with the internal parts of MHF include failure of rabble arms and teeth, hearths and refractories.

It is quite difficult after a variation to reach again stationary conditions because sludge requires more than one hour to reach the combustion zone. Therefore, the effects of control measures can be detected with delay.

Combustion can be controlled by several means. The most used parameters include hearth and outlet temperature, oxygen content in the outlet gases and air flow rate, centershaft rotational speed.

Temperature on the different hearths is measured by thermocouples. It can be varied rapidly if a burner is present at that location or at the hearth below it.

A drier cake requires addition of supplemental dilution air to avoid a migration of the burning zone upward with a corresponding increase of the outlet temperature, while a less concentrated sludge implies consumption of auxiliary fuel in the burning zone.

Oxygen content in the outlet gases is indicative of the excess air amount entering the furnace. For a non-autogenous sludge, oxygen concentration in the outlet gases should be higher than 6 % by volume which means operation at an excess air of about 60 % with respect to the stoichiometric value. Oxygen concentration shows a remarkable increase when DM overcomes the limit for autothermal combustion due to dilution air.

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Combustion air is generally controlled considering an excess air with respect to the stoichiometric value of about 100 % and more. It follows that exhaust gas production in MHF is more abundant than in FBF.

The cooling air of the shaft is partially used as combustion air at 180 °C to 230 °C. Centershaft rotational speed can be manually controlled to move the burning zone downward (increase in rotational speed) or upward (decrease in rotational speed) and to control the sludge blanket on the hearths.

8.5 Pyrolysis

Pyrolysis can be applied to dewatered sludge that has reached the self-sufficient heat level or to dried sludge with DS content above 65 %. The exhaust gas contains partial combustion products which generally makes its further purification economically not viable so that its energy must be recycled directly.

Coupling of pyrolysis and incineration can be made in a unique furnace.

8.6 Gasification

The control of reaction temperature of gasifier is more important or equal to that of other thermal treatment technologies. The volume of air supplied should be carefully controlled by the reaction temperature as well as the composition of fuel gas generated. This process generates not only a fuel gas but also a scrubbing wastewater. As the fuel gas contains combustible gases such as hydrogen and carbon monoxide, it is recommended to be properly treated. The scrubbing wastewater should be also properly treated because it contains some toxic substances to be further controlled like cyanide (CN^-) and hydrogen sulfide (H_2S). See 10.2.1. The scrubbing wastewater can be returned to the head of the wastewater treatment process directly or after pre-treatment or fully treated separately. The number of gasification plants is low but one can refer to cases studies in Annex C.

8.7 Thermolysis

On thermal and technological grounds, thermolysis is implemented with sludge dried at more than 90 %. Depending on the temperature, thermolysis results in liquid biofuel obtained by condensing the synthetic gas or syngas which purification is difficult.

8.8 Carbonization

As the bio-charcoal is a self-heating substance, it is necessary for operation and maintenance of the carbonization system to consider a comprehensive and reliable safety measures from the planning and designing phase, with well-understanding of the characteristics and heating mechanism of bio-charcoal. Bio-charcoal can be stored longer than dried sludge or so, while a strict daily management for its storage and transport is essential against the prevention of heating. In addition, the management of sludge quality and the carbonization temperature are important because the quality of bio-charcoal is much influenced by fluctuation of sewage influent and seasonal change.

The carbonization system is generally maintained through annual regular maintenance works and usual repair works. Its operation rate should be kept higher because the consumption of auxiliary fuel as well as power is higher when it is operated in low load or intermittently.

Other characteristics are described in 8.5.

8.9 Wet oxidation

Wet oxidation is used on sludge of DS concentration above 5 % and possibly up to 15 %. Its application is in addition restricted due to problems arising from pressure conditions and from deposition due to precipitation. The pressure-temperature combination should be adjusted to the sludge type.

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The wastewater produced contains ammonia in high concentration, that requires downstream treatment.

8.10 Melting

As the melting furnace is operated under high temperature, the furnace consists of heat resistance structure by using brick or refractory. Melting slag directory contacts with refractory and the refractory can be eroded by the reaction of both sludge components and refractory components. Therefore, it is necessary to repair regularly even applying anti reaction material for refractory component and/or protection by adequate refractory cooling. Since raising operation temperature to more than necessary temperature erodes refractory rapidly, it is necessary to monitor and control furnace inner temperature not to raise too much over melting point of inorganic matter.

Too frequent starting up and shutting down cause thermal contraction of refractory, which might crack or fall down. It is therefore better to ensure continuous operation plan. The component which is evaporated into flue gas in the furnace is solidified again through flue gas heat recovering and treating, then melting fly ash is produced. The melting fly ash is easily accumulated in the heat recovery equipment, flue gas treatment equipment and flue gas duct, so it is recommended to monitor flue gas temperature and flue gas pressure drop and to remove fly ash by using soot blow in order to prevent fly ash accumulation problem.

8.11 Pasteurization

Operation requires skills such as boiler operation and understanding of high-temperature and pressure processes.

Pasteurization is mainly applied when a higher hygienic quality is required for sludge reuse.

8.12 Hazards

Hazards to be considered include:

— Hazardous gaseous emissions: an important constituent of produced gas is carbon monoxide (CO) which is extremely toxic and dangerous. However, for gasification/pyrolysis systems generally working under suction, in case of gas leak no dangerous gas escapes from the device during operation. If CO emission should unlikely occur, problems could arise only in the immediate vicinity of the plant because CO quickly reacts with atmosphere O_2 to form CO_2. This aspect is of particular concern during start-up and shut-down periods, thus suggesting installation of venting systems or a chimney or in well ventilated buildings.

— Fire and explosion hazards: fire hazards may result from high surface temperature of equipment, risks of spark during refuelling, and flames emerging from air inlets. However, relatively simple safety measures are able to eliminate above risks. Gas explosions may also occur if hot gases are mixed with sufficient air amount to cause spontaneous combustion.

— Hazardous liquid effluent emissions: this includes production of ashes, which can be disposed of in the normal way, and tar/phenol containing condensates, whose amount is depending on equipment type. Amounts from down-draft gasifiers are generally small, so tar/phenol contamination is relatively minor, while large quantities derive from up-draft and open-core systems, thus requiring introduction of appropriate disposal systems.

9 Management of energy and secondary resources

9.1 General

In addition to electricity and heat, a large number of products can be recovered, depending on the process, from sludge, including phosphorus, oils, liquid and solid residues, gases, building materials, coagulants, etc.

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9.2 Drying

Energy is supplied for drying. Requirements depend on technologies.

To reduce auxiliary heat energy, it should be important to recover heat from dryer system. Moreover it should be considered to supply waste heat such as low temperature hot water and natural heat source. Generally, drying process involves several heat recovery methods.

9.3 Hydrolysis

Hydrolysis serves to increase the biogas production in the downstream treatment.

9.4 Incineration

The combustion of organic matter is an exothermic process, i.e. heat is generated and is transferred to the flue gases which can allow heat to be potentially recovered before being discharged into atmosphere.

The recovered energy can be used for several applications, including.:

— pre-treatment of sludge;

— in-process heating;

— steam production;

— electric energy production.

Products from the sludge thermal processes contain resources such as phosphorus at high concentration. For instance, phosphorus can be recovered from incinerated ash using acid and can be concentrated into slag through melting process. When these recovered materials are processed as fertilizer ingredients, the content of harmful substances including heavy metal needs to meet the quality standards in each country or region.

Ash can be also valorised as construction material, filling product and additive in cement production by means of treating through suitable technologies.

In particular, bricks produced from incinerated sludge ash do not show heavy metals leach from the finished bricks, even in adverse environments with pH levels as low as 3. The moulding process is the key to success in making the brick from 100 % ash without any additives, therefore it should be carefully carried out. Also temperature should be carefully controlled to prevent “black core”, the phenomenon that occurs when organic substances are poorly oxidized. A slow cooling cycle is then necessary to avoid breaking from thermal strain. The properties of the sewage sludge brick are superior to those of traditional bricks in all respects, including compression strength, water absorption rate, abrasion strength, and bending strength; however, problems of moss growth, ice, and whitening appeared.

Pumice is manufactured using the same approach as sewage bricks, with the addition of crushing and sieving processes. Pumice is a possible substitute of volcanic gravel used for the underlayer of athletic fields.

When volume reduction and the immobilization of heavy metals are the primary aims, slag is a possible solution because the volume can be reduced to only 4 % of the original one. Operational data showed that 80 % of the metal elements included in the sludge cake remain in the ash, provided that an appropriate temperature of the incinerator is maintained. Two different kinds of slag can be manufactured: water-cooled slag and air-cooled slag. Both varieties are vitreous, and meet the standards of the crushed gravel used for concrete, but their compression strength is not comparable to that of natural gravel. Air-cooled slag is used as a substitute for natural coarse aggregate, including concrete aggregate and back-filling material, ready mixed concrete aggregate, roadbed materials, permeable pavement, interlocking tiles and other secondary concrete products.

Other obtainable product is an artificial lightweight aggregate (ALWA). Compared with commercially lightweight aggregates, this ALWA has greater sphericity, lower specific gravity, and less compressive

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strength. Major reuses include fillers for clearance between kerosene storage tanks and room walls, planter soils, flower vase additive, thermal insulator panel, substitution of anthracite media of rapid sand filters, water-infiltrating pavement. Because of its elasticity, attractive appearance and avoidance of rainwater pooling, this material can be used for walkways pavement.

A further potential use for the sludge is as a substitute raw material for Portland cement in replacement of portion of major ingredients, such as CaO, SiO_2, and F_2O_3, traditionally supplied in the form of natural limestone and clay. Manufacturers accept incinerated ash, dried sludge, or dewatered sludge cake, depending on the operation type; the concentration of P_2O_5 is the most important factor to be considered for this application.

In all cases, the environmental and economic aspects in the specific situation should be carefully evaluated.

Heat recovery process from low quality energy source such as incinerated exhaust gas and scrubber wastewater with low temperature is now available. The Kalina cycle is utilized to generate electricity in combination with low boiling point substances such as freon and ammonia. See Annex C for more details.

9.5 Pyrolysis

Pyrolysis could be attractive because solid or semi-solid biomasses can be converted to liquid products with consequent advantages in transport, storage, combustion and flexibility in production and marketing. In transport the bulk and energy densities of the material are important, so oil and slurry mixtures have a clear advantage. Storage and handling are also important because of seasonal variations in production and demand.

The liquid product is a dark brown oil composed of highly oxygenated hydrocarbons with an appreciable proportion of water. Solid char may also be present. These properties can make it relatively unstable in both chemical and physical terms and could cause some problems in utilization and upgrading. Characteristics which affect its utilization are water content, particulate level, oxygen content, pH polymerization at temperatures above 100 °C, compatibility with conventional fuels.

The easiest way to utilize the fuel is to use it in combustion process. Alternatively, the oil can be upgraded to either a special engine fuel or converted into a syngas through a gasification process and, thereafter, to biofuel.

The devolatization of biomass during pyrolysis reactions yields a solid residue, known as char. An outlet for the char might be slurrying it with the oil, or with water, or both. Applications for the char depend on the composition and local regulations. Landfilling is problematic due to the residual heating value. Co-combustion in a power plant or waste incineration facility is an option. Another possible application is as a carbon-sequestering fertilizer or soil amendment. Here, since pyrolysis is associated with lower reactor temperatures and the absence of oxidizing conditions, the composition of the char should be carefully examined with respect to pollutant limits.

The produced gas may be used to drive the pyrolysis process if an indirectly heated process is used, or it can be employed to dry the feed, or generate power. It is usually used for drying or heating the biomass/sludge.

In addition, to syngas use for directly manufacturing products, each individual component of syngas might be isolated and purified for other purposes, such as:

— hydrogen: electricity generation, transportation fuels;

— nitrogen: fertilizers, pressurizing agents;

— carbon monoxide: chemical industry feedstock, fuels;

— carbon dioxide: injection into sequestration wells;

— minerals and solids: slag for road beds;

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— sulfur: chemical industry.

The volatiles from the process (vapours, permanent gases, tars) can be directly combusted to offset the heat requirement of the upstream sludge dryer or the pyrolysis reactor. Since a large portion of the energy content of the sludge remains in the char, a notable overall heat deficit can exist in the combined drying and pyrolysis treatment system when applied to dewatered sewage sludge (with e.g. 75 % moisture at dryer inlet).

Liquid or gaseous products are easier to handle in the combustion process and this is particularly important in retrofitting existing equipment without major reconstruction of the units, while bio-oils, char-oil slurries and char-water slurries are likely to require only relatively minor modifications of the equipment or even no modification in some cases. Gas turbines can be readily fired with bio-oil and slurry fuels although care is needed with the alkali ash residue in the char content of the slurry.

9.6 Gasification

The gasification process uses heat, pressure and steam to convert solids into a syngas which is a mixture of CO, H_2 and other gases, and other by-products like ash, char or slag, oils, and reaction water.

Syngas, whose heating value from sewage sludge is typically between 4 MJ/m^3 to 20 MJ/m^3, can be used to produce electric power, valuable products such as chemicals, fertilizers, substitute natural gas, hydrogen, steam and fuels.

The direct use of the gas in a furnace is the simplest application as it generally requires little or no gas treatment, except for dust removal. For efficiency reasons, a close coupling of the gasifier to the furnace is required.

The gas product can be used directly as fuel in combustion engines or can be further processed for chemicals or liquid fuel synthesis.

Combustion in a gas turbine is potentially very attractive due to the favourable properties of gas turbines themselves, such as low cost of maintenance, potential high inlet temperatures favouring high thermodynamic efficiencies and the possibility of using the exhaust gas in a steam generation cycle (combined cycle).

Using of gas in internal combustion engines is possibly the most attractive way of generating shaft power or electricity from biomass, unless minimum gas quality requirements are got, with special reference to dust and tar.

According to operators of wastewater treatment plants, the recovered energy, the plants' own consumption for sewage sludge drying and operation of the gasifier can almost be covered. The gasification process, finally, has an almost equal energy balance for the thermal treatment of anaerobically stabilized and mechanically dewatered sewage sludge. No surplus energy can be exported from the process.

Municipal sewage sludges contain significant portions of ash (20-50 %w dry), which represents the main by-product of the gasification process. Adequate solid residence time in the reactor maximizes the carbon conversion of the char and thus improves the overall conversion efficiency. The produced solid residue has high adsorption property when a proper activation is carried out. Ash from municipal sewage sludge contains high concentrations of phosphorus comparable to a low-grade phosphate rock ore, and can so be considered as a possible fertilizer feedstock.

Most gasifiers also produce a glass like by-product, called slag. The occurrence of the slag depends on local temperatures and the so-called ash melting point.

With gasification, sulfur is removed as elemental sulfur or sulphuric acid. Other secondary products from gasification include methanol, fuel alcohol, and ammonia.

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9.7 Thermolysis

Thermolysis may produce synthetic gas or biofuel.

9.8 Carbonization

Bio-charcoal can be utilized in and outside the treatment plant because it is odourless and porous.

The easiest way to utilize bio-charcoal is as fuel in combustion process (see 9.5). It can also be utilized for soil reclamation material and fertilizer because it contains more phosphorous than wooden-charcoal and plant-derived activated carbon. It can also be used for a dewatering aid in dewatering process.

For gaseous and liquid residues generated from the carbonization system, see 9.5.

9.9 Wet oxidation

Being an autothermal process, the process does not require, except during start-up, any external heat to keep the system at required temperature. This is achieved first by using heat exchangers to recover heat in mineralized sludge and secondly by the heat released by exothermic oxidation reactions.

Heat can be recovered directly by heat exchange in the reactor, or from the effluent leaving the reactor, while inorganic components, like phosphates and/or coagulants, can be recovered from the process effluent which consists of a slurry of inorganic ash in a water phase.

The aqueous stream contains about 20 % of the original organics in the sludge and significant quantities of nitrogen, so it is either returned to the head of the wastewater treatment plant or treated separately and discharged. The residual solids, mainly consisting of carbonates, silicates, phosphates and non-leachable heavy metals, complies with the criteria of landfilling for inert waste or non-dangerous waste. Energy can be recovered from the system, as hot water.

9.10 Melting

The types of slag obtained by cooling melted sludge are roughly divided rapid cooling and gradual cooling slag, and its character are different. Major cooling methods and slag characters are shown in Table 3.

Slag may be utilized road material, backfill material and/or resource material of concrete secondary product.

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Table 3 — Types of slag and their characteristics

Cooling type	Slag type	Cooling method	Slag character
Rapid cooling	Water cooled slag	Melted slag is cooled in the water or cooled by cooling media indirectly.	Slag structure is vitrified and is brittle. The shape of direct water cooling slag is granular.
Gradual cooling	Air cooled slag	Melted slag is poured into the cast iron mould etc. and cooled by atmosphere.	Slag structure is vitrified but its hardness is better than water cooled slag.
	Slow cooled slag	While radiation heat from melted slag is controlled and/or slag temperature is controlled, slag is cooled during long time.	A part of slag structure forms mineral crystal therefore hardness is more than air cooled slag. The shape is crush stone like.
	Crystallization	Water cooled slag or air cooled slag is kept under 900 °C to 1 000 °C while a certain period and is crystalized.	Dense crystal is formed in the slag and slag has strong hardness and acid resistance.

9.11 Pasteurization

Pasteurized sludge may be used as fertilizer in agricultural lands.

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9.12 Thermal treatments and circular economy

Thermal treatments can be compared according to criteria related to a circular economy as aggregated in Table 4.

Table 4 — Energy production, nutrient recovery and product valuable out of the plant by technology

Technology	Energy production	Nutrient recovery	Product valuable out of the plant	
			Products with low/no market value	Valuable product
Drying				Biosolid as fertilizer
Hydrolysis	Through biogas production in downstream digestion		Carbon resource for denitrification	
Incineration	From heat recovery in flue gas	P recovery under phosphate in fly ash	Ash used as material construction	Residual heat Electricity
Pyrolysis	Electricity and heat from syngas	Biochar as soil conditioner or fertilizer	Sulfur	Bio-oil Syngas Char for sorbent production
Gasification	Electricity and heat from syngas	Biochar	Slag used in construction materials	Residual syngas
Thermolysis				Biofuel
Carbonization				Bio-charcoal
Wet oxidation	Process heat from hot water			
Melting			Slag used in construction materials	Possibly, slag as raw matter for fertilizer
Pasteurization				Stabilized pasteurized sludge for land application

10 Management of residues

10.1 General

Residues include flue gas, ash, and wastewaters. They are discussed in the following subclauses together with equipment for their treatment which are all relevant to thermal processes, unless differently stated.

10.2 Flue gas

10.2.1 Characteristics and parameters

Pollutants in flue gas include particulate matters, carbon monoxide, sulfur oxides, hydrogen chloride, nitrogen oxides, toxic organic compounds, H_2S, CN and trace elements.

Particulate matter

Particulate production from sludge thermal processing varies widely, depending on sludge nature and feed rate, device type, operating temperature, turbulence and residence time. Additionally, if semi-dry or dry systems are used, the separated particulate matter includes also the reaction products.

Either wet systems or dry systems can be used to remove particulate.

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Sulfur oxides (SO_2) and hydrogen chloride (HCl)

Wet scrubbing systems, like those used to capture particulate, and packed towers can be used to absorb acidic gases. Alkaline products are often added to water for enhancing removal efficiency of SO_2; the mechanism of removal is absorption with chemical reaction. Reductions in the effluent up to 15 mg/m^3 measured under normal conditions of temperature and pressure for SO_2 and 7,5 mg/m^3 measured under normal conditions of temperature and pressure for HCI are easily obtainable. In FBF operation a capture of SO_2 and in lesser extent of HCl can be performed directly in the furnace by an addition of lime and calcium carbonate to the bed.

Alternatively, the abatement of sulfur derivatives may be based on catalytic processes thus chemically reducing the pollutants to the elemental state.

Nitrogen oxides (NO_x)

Nitrogen oxide production in sludge combustion depends mainly on temperature, air distribution and nitrogen concentration in the solids and water matrix of feed sludge.

Nitrogen oxides (NO_x) in exhaust gases are mainly constituted by NO and in much minor quantity by N_2O and NO_2, which, conversely, is much more toxic. The main mechanisms responsible for NO_x production are:

— oxidation of nitrogen gas at high temperature that becomes noticeable when temperature rises to 1 200 °C to 1 300 °C;

— oxidation of organic nitrogen compounds present in sewage sludge.

The release of N_2O during sludge incineration could significantly contribute to the problem of greenhouse gases emissions. Nitrous oxide, N_2O, production during sludge combustion depends also on temperature, air distribution and nitrogen concentration in the solid and water matrix of feed sludges. N_2O has approximately 300 times as high as CO_2 in greenhouse gas effect. N_2O can be degraded using high temperature combustion over 850 °C. Countermeasures such as raising temperatures in the secondary chamber (free board temperature in FBF) and multi-air blowing in FBF are adopted.

Organic compounds (including odours)

They can be reduced through afterburning which is particularly recommended for MHF, possibly not necessary for FBF, if proper operating modalities are guaranteed.

Other option is the adsorption of organic substances on adsorptive media, such as activated carbon (the most widely used due to its low affinity for moisture), active coke, lime and their mixtures, silica gel, aluminium oxide and magnesium silicate.

This operation can be performed either in dedicated vessels (which allow also the regeneration of media) or by direct addition into the gas stream before the particulate removal devices.

H_2S, CN and ammonia

Toxic gases in combustible gas generated in pyrolysis, carbonization and gasification processes.

Toxic gaseous substances such as cyanide (CN-), hydrogen sulfide (H_2S), ammonia (NH_3) are, especially, co-existing in the combustible gas generated in the process of pyrolysis, carbonization and gasification because the oxidation reaction is minor in such thermal treatment processes. These toxic gases should be removed from the gas stream by means of a proper combination of after-burning, catalytic reaction, water scrubbing. Residual waste and wastewater stream should be also appropriately treated because of their toxicity.

The concentration of the toxic substances washed out into a wastewater stream should be properly monitored and controlled in accordance with the discharge limits of each country or environmental impact.

Trace elements

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Heavy metals are generally associated to particulate matter, and emission depends on their volatility, combustion temperature, and presence of other chemical species, like chlorine, which are able to form volatile compounds.

Metal volatility, typically decreases according to the sequence Hg, As, Cd, Zn, Pb and Cu. Metal and compound volatilisation is likely to occur when boiling temperatures do not exceed operating combustion temperature by more than 90 °C. Beyond temperature, other factors have influence on metal volatilisation with particular regard to the presence of chlorine, which can increase volatilisation of Cd, Zn, Pb and Cu, and to the presence of pyrolysis pockets in the combustion chamber, which could be a critical factor for Zn.

Mercury is the most volatile metal and can pose severe problems depending on concentration in sewage sludge. Implementation of special removal system is recommended at the installation.

Co, Cr, Cu, Fe, Mn and Ni can be considered non-volatile metals and their appearance in the emissions that can be accounted for 2 % to 11 % of the feed metal, is linked to the particulate presence. Their concentrations in the bottom and fly ashes of the incineration furnace do not depend on its operating mode.

10.2.2 Equipment

Equipment for flue gas purification can be classified in two main groups:

— units which are able to separate solid particles;

— units which reduce gaseous contaminants by absorption, adsorption and/or chemical reaction.

The equipment for solid particle entrapment includes:

— impingement separators;

— cyclones;

— electrostatic precipitators;

— bag filters/ceramic filters.

Above equipment are generally able to remove particulate down to 5 to 40 mg/m^3 measured under normal conditions of temperature and pressure, mainly depending on the particle size.

Impingement separators are essentially a series of baffles placed in the gas stream which allow particulate to be deposited on.

Cyclones are cylindrical or conical static chambers, where flue gases enter tangentially and solids particles are collected on the walls due to centrifugal force and then discharged from the bottom. The effectiveness of dry cyclonic separators on particles smaller than 15 µm is negligible, so they are often used coupled to other devices.

Electrostatic precipitators involve formation of gas ions, charging of particles, migration of charged particles toward a collecting electrode, neutralization of charge and collection of separated particles. Between emitting and collecting electrodes a voltage of 20 kV to 100 kV is applied and this determines a strong electric field close to the emitting electrode (about 20 kV/cm) and a lower field in the vicinity of the collecting one (about 2 kV/cm). A strong ionization of dust particles is induced and they move towards the collecting conductive electrodes. System efficiency is strictly connected to the removal of particles from the collecting surface. The most common removal devices are rappers; another method is to wet the collecting surfaces down. Electrostatic precipitators are effective for particulate removal including small size particles down to sub-micro metres range. Another key parameter is the particle resistivity: if it is high, particles are unable to get electrically charged.

Fabric filters or baghouses are a series of permeable bags; for this application polytetrafluoroethylene (PTFE) is the typical material used to make the bags, which allow the passage of gas but not of particulate matter. Because of the pressure drop increase with filtering time due to dust accretion

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on the bag cloths, systems for surface cleaning are necessary: they include shaker mechanisms, compressed air, re-pressurization and sonic apparatuses. Particles larger than 1 µm can be caught by fabric filters or baghouses. A temperature control of the inlet gas stream is needed to avoid possible damage of the filtering cloth. Meanwhile several kinds of ceramic filter were made available for higher temperature resistance.

The systems used for gaseous contaminant abatement are generally subdivided in dry, semi-dry and wet systems.

In the dry systems, dry chemicals (generally lime or sodium bicarbonate and activated carbon) are introduced into a ductwork or a reaction tower or a recirculating system to have minimum two second of reaction time. The gaseous pollutants are removed by adsorption and chemical reaction. Chemicals and reaction products are then removed by a system for particle separation.

In semi-dry system, slurry is introduced into the reactor. The significant heat of the exhaust gases produces a complete evaporation of the liquid (water) in the slurry and therefore no liquid side-streams are generated. The mechanism of removal of contaminants is the same of that of the dry system. Both in dry and semi-dry systems careful control of material dispersion in the reaction zone and the recycling of the reaction products and of the excess reagent minimize chemical consumption and prevent abundant production of fly ashes. In this case chemicals consumption can be lowered to 1,5/2 times the stoichiometric need.

In wet devices, particles are firstly wetted by contact with liquid droplets and then impinged on a collecting surface. Acidic compounds in presence of water can result in significant acid formation with corrosion problems.

Wet cyclone collectors are basically dry cyclones provided with a water spray. Venturi scrubber is a throat where gases pass at high velocity in the range of 50 m/s to 180 m/s, through a contracted area which is followed by an expansion section for separation of particles; water is injected at the throat or just upstream of the Venturi section. The area ratio between the inlet and the throat typically is 4:1. The high velocity gas atomises the liquid into the gas stream. This type of device can be used both for gaseous contaminant and for particulate removal. The collection of the fine particles by the liquid droplets is accomplished by inertial impact during the time the droplets are being accelerated until their velocity approaches that of the gas. At this point the probability of inertial impaction (downstream from the throat) decreases rapidly[1)].

Tray and packed towers can be used for gaseous pollutant removal by liquid scrubbing which involves bringing the dirty effluent gas into contact with the scrubbing liquid. High interfacial surface area, turbulence and large mass diffusion coefficients accelerate absorption. Both in tray and packed towers gas enters the bottom and the clean gas exits at the top of the tower. Conversely, clean liquid enters the top and is withdrawn from the bottom. Tray scrubbers consist of a tower equipped with perforated plates and target baffles; while packed towers are columns with one or more zones full of packing elements. The purpose for scrubbers is gas cooling, trace elements condensation, due to the low temperature of exit gases (60 °C to 70 °C), HCI, HF and SO_2 scrubbing, residual particulate removal, odour control and, to a lesser extent, Volatile organic carbon removal.

The chemicals consumption in wet device systems is only 10 % higher than the stoichiometric need.

Activated carbon adsorption can be used to remove organic micropollutants, with molar mass higher than 200, and mercury emissions. The adsorption process is discontinuous. The advantage of the physical adsorption is that the process is reversible. By lowering the pressure of the absorbate in the gas stream or by raising the temperature, the adsorbed contaminants can be desorbed without a change in chemical composition. Regeneration process is nowadays not carried out in the incineration plants because of economic aspects.

1) The corrosive effect exerted by the gas/liquid mixture passing through the throat should be considered. This problem can be controlled by a careful addition of water together with a proper design of the Venturi throat (velocity, use of synthetic material).

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The general characteristics to be considered in the design or selection of suitable adsorption equipment include:

— provision for sufficient residence time;

— adequate pre-treatment to remove high concentration of competing gases by other more effective and less expensive process;

— good distribution of flow through the bed;

— provision for renewing or regenerating the adsorbent bed after it has reached saturation.

In other processes addition of coke/activated carbon with lime is carried out together or separately in a spray dryer. This allows to reduce the problems of possible ignition of pure coke or activated carbon.

NO_x emission control can be performed by catalytic processes (SCR) or by non-catalytic processes (SNCR).

SCR is conducted by impacting in the gas stream a reducing agent, generally ammonia or urea, in presence of a catalyst, which is generally based on the use of metals such as nickel, platinum, palladium, vanadium, with formation of H_2O and N_2.

Chemical reactions occurring in the process are the same of the SNCR one, but at a lower temperature (ranging about 300 °C to 400 °C) and with higher performances (about 80 %). Denox systems which can operate at lower temperature (around 170 °C to 180 °C) are available on the market.

The catalyst has the tendency to become poisoned by the formation of ammonium sulfate that is formed on the catalyst in the presence of SO_2. A preliminary abatement of this contaminant is, therefore, very important.

SNCR is based on the reaction of ammonia or urea with NO_x with production of nitrogen gas at temperatures of 800 °C to 1 100 °C. The dilute solution is injected, atomised with pressurized air, in the hot gases. This produces radicals NH_2 which react with NO_x bringing to formation of N_2, H_2O, CO_2 and minor quantities of NH_3. Efficiency of the process depends on the dosage of the reactive chemicals, on the injection point and on the mixing conditions between the reactive chemicals and the gas stream[2)].

Performance of SNCR is considerably lower than that of SCR. NO_x concentration in the treated stream can be hardly reduced down to 150 mg/m^3 measured under normal conditions of temperature and pressure.

Flue gas recycle, or oxygen control, can help in reducing NO_X production. Normally, more secondary air is required to provide turbulence than is needed for supplying oxygen. Flue gas re-circulation replaces 10 % to 20 % of secondary air, reducing oxygen and peak temperatures thereby reducing NO_x formation.

The injection of ammonia can avoid the formation of dioxins in the cooler parts of the circuit. However, the production of N_2O can increase.

10.3 Ashes

10.3.1 Composition/parameters

Typical composition of ash is shown in Table 5[3)].

2) A capture system of NH_3 should normally be considered with respect to current and future limits at the emissions.

3) Attention to the quality of the bottom ash from a MHF should also be paid as far as TOC content is concerned.

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Table 5 — Matrix elements in sewage sludge ashes (DM)

Values in %

	Min.	Max.	⍰	Median
Al_2O_3	1,3	38,1	9,7	9,1
CaO	8,5	52,9	19,3	14,7
Fe_2O_3	2,6	29,0	14,1	13,6
K_2O	< 0,008	2,0	1,0	1,1
MgO	0,5	6,5	2,3	2,2
Na_2O	0,2	3,6	1,0	0,8
P_2O_5	3,4	30,0	16,8	18,1
SO_3	0,8	17,1	3,6	2,4
SiO_2	5,2	51,8	26,4	26,3
TiO_2	0,1	2,5	0,6	0,6
ZnO	0,1	0,7	0,3	0,3

Metals likely condense onto fine particulate matter and therefore small, respirable-sized particles tend to have the highest metal concentrations. Moreover, toxicity might also depend on the actual form in which the metal is present (see different carcinogen potential of chromium VI and III) and, consequently, on its availability.

The metal concentration of ashes is generally different from that of feed sludge: there may be an enrichment, due to the reduction of loss of ignition, and in some cases a reduction, due to the loss in the emissions in gaseous form or in particulate.

Frequent analysis of ash is needed to confirm effective burnout (1 % to 3 % residual carbon or 5 % of loss of ignition is common in incineration processes, but 0,1 % could be achieved).

In some incinerator the flue gas treatment is a two steps process:

— ashes separation (e.g. cyclone or ESP);

— acidic gas neutralization and capitation of reaction products (e.g. baghouse filter).

10.3.2 Processes and equipment

Bottom ash can be discharged from the furnaces by mechanical or pneumatic (dry methods) or hydraulic (wet method) systems.

The dry ash handling systems are particularly suitable when the ultimate disposal site is far from the plant and a long storage time before disposing of occurs.

Dry systems should ensure that dust does not become airborne. This can be accomplished either by proper containment or by dust suppression sprays. Spraying should be limited to ensure they moisten and agglomerate the ash without leading to leachate problems. If handled wet, the ash should be drained before leaving the site.

Wet handling systems can create several problems, such as wear of pumping and piping equipment, plug-ups at bends or restrictions and corrosion above slurry vessels. Control of trace elements concentration in the wastewater to be disposed of is very important to respect standard limits.

Fly ash should be stored and transported in a manner that prevents fugitive dust releases. During silo and container filling, displaced air should be ducted to suitable dust arrestment equipment.

In generally and especially for P recovery in view of a recovery of valuable elements (P, K and metals) from sludges, it is appropriate to keep fly ash and bottom ash separated.

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10.4 Wastewater

Wastewater is mainly originated from bottom ash quenching and wet gas treatment (e.g. by scrubbers).

Wastewater may also derive from several other points, such as the fly ash handling system, various sluice-ways and fly ash conveying.

Depending on the liquids used and the gaseous contaminants removed, wastewater can contain chlorides, sulphites, sulphates, phosphates, particulate matter, heavy metals and trace elements, at levels that require treatment to comply with standards for discharge into sewer systems or receiving water bodies.

If the stream contains little biologically degradable organic substances, physical-chemical processes are usually enough to achieve the required quality standards for the effluent. The usual treatment sequence is coagulation, flocculation and settling. In the case of higher amounts of biologically degradable organic substances, a specific treatment should be applied.

In case trace organics are present (such as dioxins, furans, polychlorinated hydrocarbons, phenols) appropriate treatments, e.g. filtration and subsequent activated carbon adsorption units, are required.

Recirculation which is not a dilution process can be adopted to minimize the amount of water to be discharged. Wastewater from bottom-ash quenching is recycled after chemical-physical treatment and the make-up water is in the order of 20 % maximum the total water consumption.

11 Decommissioning of installations

11.1 General

Sewage sludge incineration facility can be operated during 15 years to 20 years by proper repair and maintenance. This clause describes the aspects to be considered in the decommissioning of an incineration facility.

11.2 Specific considerations

Due to little chlorine component content in sewage sludge, the synthesis of dioxins seldom happens by incineration, for example, in case of the fluidized bed furnace which can achieve the complete combustion. In addition, the concentration of dioxins in flue gas and ash is not at a level that causes a health hazard under normal operation. However, there is possibility for accumulation of the slightly contaminated substances by a type of furnaces or at some specific parts where might have stagnation of the flue gas such as ducts or scrubber. Therefore, in case of the decommissioning work for the above-mentioned parts of the incineration facility, the demolition work should be done with care not to spread contaminants into the surrounding environment.

a) The purpose of the prevention of exposure in decommissioning covers the following.

   — Confirmation of the contamination by dioxins.

   — Prevention of the dioxins contaminant exposure into the environment other than the decommissioning facility area.

   — Prevention of the dioxins contamination from persons working for decommissioning.

   — Prevention of exposure to particulates for workers.

b) The procedure of decommissioning includes the following.

   — Planning of the decommissioning work.

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— Implementation of the decommissioning work.

Based on the decommissioning work plan, the work should be implemented, preventing any contamination of the environment and workers by enclosing its work area and using an appropriate protective equipment and any other necessary tools such as artificial breathing apparatus.

— Appropriate treatment of the decommissioning waste.

In order to prevent the exposure into the surrounding environment, the following treatments are necessary; an appropriate treatment of exhaust gas, waste water, and waste materials discharged from decommissioning work area. In addition, an appropriate treatment for contaminated materials is also required, such as protective suits and any other tools which are used during the decommissioning work.

12 Co-management with other organic wastes

12.1 General

From a general point of view, wastewater sludge generally has a high water content, and in some cases high levels of inert materials, so its calorific value is often low. By combining sludge with other combustible materials in a co-management scheme a feed having both a low water content and a heat value high enough to sustain combustion with little or no supplemental fuel could be created.

Common materials for co-management schemes are MSW, agriculture wastes, coal and wood. However, each case is differing from others as a consequence of different qualitative and quantitative characteristics of wastes involved; it is, therefore, impossible to make considerations applicable to all possible situations, so in the following the co-management of sludge with MSW is more extensively discussed.

Further, co-incineration of sewage sludge with MSW or coal may have cost advantage over mono-incineration, depending on supply and transport factors.

In addition to above general considerations, reasons which lead the decision-makers to choose combined treatment of sludge and other organic waste derive from several considerations including:

— the impossibility to apply any other process or the availability of alternative already existing solutions, throughout whole or part of the year, in particular in the case of technical shutdown;

— the geographical, economic and social contexts, as well as the expected developments;

— the proximity of the sewage treatment plant to the thermal treatment plant and the local road network;

— the extent to which the thermal treatment plants are used (capacity of devices, charge levels, etc.);

— the variations due to seasonal activities and production peaks both in sludge and other organic waste.

Considering combined treatment as one of the options for sludge management, two approaches are possible:

— the treatment site accepts over the course of time materials of different origin, type, and quantity, and should be readily adaptable to guarantee in any case optimum performance;

— the treatment site does not offer any flexibility, so a quantitative or qualitative limitation is be demanded on the site, and a reflection, taking into account the technical and economic constraints, should be conducted in order to examine the influence of any modification in sludge production to achieve a perfect material/process match.

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Finally, it is worthwhile specifying that thermal plants are installations which, for technical and maintenance reasons, operate between 7 000 h/y and 8 000 h/y, so it is advisable to provide for a selective and appropriate organization with the water treatment site administrator during the plant shutdown periods, particularly in the case of a plant equipped with one treatment line only.

Under these conditions, it is then a question of knowing the sludge parameters and characteristics which can influence the combined treatment process with a view to making provision for the necessary installations, the behaviour and flexibility of the equipment to be implemented, as well as the possible additional maintenance and wear (see Annex B).

The operational departments of the treatment plants should reserve the right to refuse a sludge, which can present one or more abnormal parameters, e.g. a particularly high content of one or more trace elements and for which the unit's equipment:

— does not allow to guarantee safe operations and compliance with current emission limits;

— generates residues whose quality does no longer allow a disposal in conformity to the provisions in force (regulation and/or current technical-economic conditions).

With specific reference to their dryness, sludge types that can be envisaged for combined management include mechanically dewatered sludge, and partially or totally heat-dried sludge using thermal dryers.

12.2 Specific considerations

Co-incineration plant can be defined as any stationary or mobile plant whose main purpose is the generation of energy or production of material products and which uses wastes as a regular or additional fuel or in which waste is thermally treated for the purpose of disposal.

Four furnace types can be mainly used for sludge/MSW combined incineration. These are:

— stoker type furnaces containing mechanical components (bars or grates) driven by a translational motion (linear movement); the grate is either inclined or horizontal (see Figure 17);

— roller furnaces comprising stepwise arranged rotating cylinders (circular movement);

— reciprocating or rotary kilns. The axis is slightly inclined to the horizontal;

— fluidized bed furnaces, which can comprise two types: bubbling fluidized beds (see Figure 12) and circulating fluidized bed (see Figure 13).

Whatever the furnace type involved, two essential functions should be combined:

— treatment of waste either alone or in mixed form, in order to convert it into ash with the lowest possible percentage of Total Organic Carbon, while avoiding the formation of more or less melted blocks of bottom ash (caking);

— distribution of the air used for combustion and cooling down of the mechanical components or of the sole plate according to two types of air versus current or combined air-current designs.

In the case of co-combustion, main advantage is that the excess heat from MSW can be recovered for sludge drying, thus allowing the need of auxiliary fuel to be reduced or avoided. Generally, a heat balance is reached when the per-capita quantities of MSW and sludge at 25 % to 30 % solids are combined. Unlikely, particulate emissions are higher, although their abatement is not a problem with modern technologies.

In any case, considered that the calorific value of MSW is usually situated between 7 000 kJ/kg and 11 000 kJ/kg, a LCV caused by the sludge/household waste mixture less than 7 000 kJ/kg should be avoided, because of the subsequent problem of complex mixing of the two wastes.

The introduction of sludge into a household waste furnace results mainly in an increase in the volume of the combustion gases, in their humidity and in their SO_2 content.

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Besides the sludge characteristics, the possible different waste-sludge combined treatment depends on the constraints resulting from the complete treatment line, taking into account the design and flexibility of the furnace-boiler-waste gas treatment facility.

The technical means for introduction wastes into the furnace are designed so as to mix in the most appropriate manner possible the sludge with the household waste and to avoid all concentration points and all risks of clogging on the refractoried surfaces of the furnace.

In all cases, the introduction of an additional waste material into the thermal treatment system should not interfere in any significant manner with the initial performance of the system.

In order to maintain satisfactory conditions and to avoid any adverse effects on the resistance of the refractory materials, it is desirable not to exceed a thermal overload and therefore an increase in waste gas enthalpy in the region of 5 %, this figure being dependent on the LCV of the sludge.

A distinction is also made between the introduction of a sludge in a paste-like physical state in a solid one (see CEN/TR 15463).

In the case of a paste-like sludge the amount of sludge which can be incinerated depends mainly on the quantity of excess air available if it is wished to maintain the furnace's thermal capacity. The quite rapid vaporization of the large quantity of water contained in the sludge increases the volume of the gas in the furnace and thus contribute to “locally cooling down” the temperature of the gases. In the case of a pre-dried sludge (around 60 % for example, an interesting case for which the calorific value of the sludge is close to that of household waste), the quantity of sludge which can be incinerated depends on the available thermal capacity, the furnace type and its mechanical functioning. At nominal operation, all additions of sludge are made to the detriment of the household waste.

In the case of sludge dried to about 90 %, the calorific value of the resultant mixture is considerably increased and only the combustion chart allows a reasonable ratio to be defined. This type of combined incineration is only used insofar as the quantity of household waste treated is less than the furnace's nominal capacity.

Particularly for this latter case, the distribution of the sludge over the bed of household waste should be well carried out in order to avoid the emergence of oxygen starved zones which can give rise to an increase in the quantity of unburned residues in the bottom ash and in the CO content in the combustion gases and a possible not homogeneous temperature in the furnace. This remark is not valid in the case of fluidized beds.

New installations are, therefore, dimensioned so as to take into account a total volume of waste gas greater than the volume given off by the combustion of household waste alone.

Concerning all the pollutants to be treated, each installation has its own limitation thresholds (or maximum pollutant load values at the entry of the purification system). It is advisable to verify the compatibility of the treatment process with the addition of sludge. Likewise, if the combined incineration is not continuous (e.g. only operates on one or two units, namely 8 h to 16 h a day) particular attention should be paid to the relevant local regulations in force for pollutant emissions - continuous, average rate per hour per day, etc.

In this latter case, care is taken to see that the furnace's regulation system manages these periods, with or without sludge, so as not to disrupt combustion and the resulting elements (gaseous, liquid and solid effluent).

Finally, in sludge co-incineration in MSW incinerators and power plants, P recovery might not be feasible, due to the dilution of the P-containing sludge ash with as from the co-fuel and to the presence of other pollutants in MSW.

Summarizing, each case is in fact a specific case, whether it is a question of existing or new installations, defined by:

— the combustion chart;

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— the furnace type;

— the possible location of the introduction system (s);

— the compliance with the “3T rule”;

— the combustion gas treatment capacity;

— the dividing up of the sludge mineral ashes into bottom ash and fly ash;

— observance of the regulations.

Additional specific considerations on co-gasification and co-pyrolysis are at the moment not available due to scarcity of experiences and lack of documented data.

12.3 Additional storage and transport aspects

12.3.1 General

In addition to storage and transport aspects already described, the following apply in the case of co-management of sludge and other organic waste, especially MSW.

12.3.2 Storage

Sludge can be stored with MSW either directly by tipping into the pit, or by using spray, or any other method in order to spread it right through the pit. Any choice depends on local situation.

Two elements are essential in the quality of the sludge to be tipped: dryness and consistency. In the case of liquid or paste-like sludge, there is a risk of MSW becoming wet and water accumulating by gravity at the bottom of the pit. An identical gravity phenomenon can occur with solid sludge of low particle size, difficult to remove with a grapple.

In all cases, tipping sludge into a pit creates an additional work for the crane operator so that the mixture is as homogeneous as possible. This work should be carried out in parallel with the management of MSW in pits and therefore requires a dual function for the crane driver.

In fact, this is a possible solution where sludge quantity is low compared to the MSW and/or on a selective basis. Depending on how dry the sludge can be and the proportions anticipated, a study should be envisaged, even prior characterization tests.

Attention should also be paid to the explosive and burning risks related to dried sludge, as well as to the odour problems, which are directly linked to the quality of the sludge (e.g. raw sludge) which leads to the calculations of the unloading hall system being revised: additional deodorization can prove necessary.

It is advantageous to store sludge on the thermal treatment plant site, because it provides a buffer between the sludge production and its treatment, which can sometimes be discontinuous. If the storage facility area is close to the treatment plant, the sludge can possibly be stored directly in this area and to feed the treatment plant by pipeline.

The storage facility area regroups sludge of different origins, irrespective of its condition. It can therefore take the form of a pit, a tank or silo. It is located within the treatment plant site perimeter in a separate properly identified area, different from the storage area where other wastes treated on the site are stored. Input to the storage facility should be either by pipeline (for liquid or paste-like sludge) or by skips (for paste-like or solid sludge).

Mention should be made of the particular case of solid sludge arriving at the site for treatment, for which a possibility of direct tipping into the waste pit can be examined.

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The sludge container should be equipped with a level measurement system or (except when it is merely a pit for which a simple visual inspection by the operators should prove sufficient) a filling system and a draining-off connection device.

Provision should be made for sludge recovery from the bottom of pits, tanks or silos. Likewise, consideration should be given to recovering water used for cleaning working areas and the containers themselves.

The storage containers should be adequately dimensioned. It is wise to have at least one storage volume equivalent to the quantities of sludge, which is treated by combined treatment over a 72 h period. This volume should be calculated on the basis of treatment device furnace operation at the constructor's rated capacity and confirmed by the operator, taking into account a nature of waste which is always highly variable and on the basis of a ratio of treated sludge to domestic refuse which is dependent on the size of the furnaces and on the principle adopted for combined treatment. The hazards relating to the supply of sludge is also taken into consideration.

Sludge mixing can also be taken into consideration, as the combined treatment plant should be capable of treating all the sludge brought to the site, i.e. from different origins and sewage plants.

The constituent materials of the equipment should be insensitive to the products being stocked in order to avoid any premature ageing.

Prior to installation, particular attention should be paid to the maintenance of the equipment.

12.3.3 Transport

Transport consists of conveying the sludge from the sewage treatment plant to the co-treatment plant, if possible in a single stage. It includes the sludge loading and unloading operations.

The transport system should be designed so as to guarantee maximum containment and limited nuisance due to smells. Transport should not give rise to any accidental spillage of sludge onto the roadways and the various manoeuvring areas. In the event of the travelling distances being long, modification of the sludge should be taken into consideration.

Vehicles used should be suited to the different categories of roads.

It is not to be forgotten that transport can be carried out via pipeline where the plant and treatment plants are close enough to one another for this to be technically and economically feasible. The pumping conditions and the outputs to be applied are then particularly examined.

Transport by barge or railways should also be considered depending on specific local situations.

13 Assessment of sustainability

13.1 General

Similarly to economic aspects, information available on such kind of assessment for thermal processing of sludge is quite limited, especially for less conventional technologies, to allow general and reliable conclusions to be drawn.

Generally, in the course of the operation of incineration installations, emissions and consumptions arise, whose existence or magnitude is influenced by the installation design and operation.

The potential impacts of thermal treatment installations involve environmental, economic, and social aspects.

Within this framework, appropriate decisions should be based on the BAT concept taking into consideration the technical characteristics of the installation concerned, its geographical location and local environmental conditions to ensure a high level of protection for the environment as a whole.

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13.2 Environmental aspects

They include (see Reference [5]):

— the evaluation of the overall process emissions to soil, water and air (including odour, greenhouse gases, dioxins and other emissions);

— the consumption and nature of raw materials and resources used in the process and their energy efficiency;

— the amount and quality of end products, process residues and/or secondary resources;

— the process noise and vibration;

— the reduction of the storage, handling and processing risks of hazardous wastes;

— the need to prevent accidents and to minimize the consequences for the environment.

13.3 Economical aspects

The advantage to adopt thermal process is mainly;

— drastic reduction of final disposed quantity;

— utilization of final products such as bio- charcoal and biosolids; and

— energy recovery (energy generation) such as electricity and bio-fuel.

The cost analysis for any thermal treatment should take into account the following:

— the overall energy balance (consumption and production) of the system considering availability and cost of energy;

— the raw material (reagent) consumption;

— the reliability of the technology;

— the recovery and recycling of substances generated and used in the process;

— the marketability of end products;

— the transport of incoming sludge and outgoing residues;

— the requirements for extensive sludge pretreatments;

— the needs in maintenance and repairing and related intensity;

— the requirement in operation staff;

— the asset management.

13.4 Social aspects

They include:

— the formation of a public consensus on the facilities installation;

— the evaluation of the level of applicability of existing regulations, rules and recommendations in the specific geographical and social contexts;

— the acceptance by local population.

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Within this framework, appropriate decisions should be based on the BAT concept taking into consideration the technical characteristics of the installation concerned, its geographical location and local environmental conditions to ensure a high level of protection for the environment as a whole.

The life-cycle assessment (LCA) technique can help avoiding a narrow outlook on environmental concerns. It allows the impacts associated with all the stages of a product life from raw material extraction thru materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling to be assessed by:

— compiling an inventory of relevant energy and material inputs and environmental releases;

— evaluating the potential impacts associated with identified inputs and releases;

— interpreting the results to help you make a more informed decision.

The main aspects to be considered in a life-cycle assessment are energy consumption and related cost and migration and transformation of pollutants both in the thermal process itself and in application or use of by-products. Furthermore, assessment of direct emissions of CO_2, CH_4, NO_x and indirect emissions derived from energy consumption, chemical agents, etc. from original sludge to application of product is also important.

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Annex A
(informative)

Calorific values calculations

As a first approximation the Greater calorific value (GCV) can be evaluated by the Du Long equation, if the elemental analysis of combustible material is known:

$$GCV = 32\,810\ C + 142\,246\ (H - O/8) + 9\,273\ S \quad \text{(A.1)}$$

where GCV is in kJ/kg LOI (organic matter), and C, H, O and S are the mass fraction of the elements in the loss of ignition.

The above formula gives an overestimation of the heat value of sludges with high organic nitrogen content because a) the nitrogen is associated with the hydrogen as an amine, and b) the production of nitrogen oxide in the amine combustion reduces the hydrogen heat release.

The following equation can be used to take into account the above effects:

$$GCV = 32\,810\ C + 142\,246\ (H - O/8) + 9\,273\ S - [2\,189\ N\ (1 - \mu) + 6\,4894 N\ \mu] \quad \text{(A.2)}$$

where μ represents conversion (mass fraction) of nitrogen to nitrogen oxide, generally in the range 2 % to 7 %.

The Lower calorific value can be evaluated by measuring the chemical oxygen demand COD and the total Kjeldahl nitrogen (TKN) (ammoniacal + organic nitrogen) and using the formula:

$$LCV = 13\,700\ COD + 19\,000\ TKN \quad \text{(A.3)}$$

where LCV is in kJ/kg LOI, and COD and TKN are expressed in kg/kg LOI.

COD of sludge generally varies in the range of 1,5 kg to 1,8 kg O_2/kg LOI and TKN in the range 0,02 kg/kg LOI to 0,09 g/kg LOI.

Typical calorific values of municipal wastewater sludges range from 22 100 kJ/kg LOI to 24 400 kJ/kg LOI (anaerobically digested primary) to 23 300 kJ/kg LOI to 27 900 kJ/kg LOI (raw primary). Secondary sludges display values between 20 700 kJ/kg LOI and 24 400 kJ/kg LOI.

The variability of the calorific value mainly depends on the elemental analysis of sludges: when the hydrogen content is higher also the calorific value displays higher values as for primary sludge in comparison with secondary and with digested sludge.

LCV can be estimated considering the water present in the sludge (1 – X), being X the fraction of dry solids, and the combustion water (9 H LOI):

$$LCV\ (kJ/kg\ sludge) = GCV\ X\ LOI - 2\,440\ (9\ H\ LOI + 1 - X) \quad \text{(A.4)}$$

where LOI is the loss on ignition with respect to dry solids (kg/kg).

If the lower calorific value of loss on ignition is known (LCVLOI) the lower calorific value of wet sludge can be easily evaluated by:

$$LCV = LCVLOI\ X\ LOI - 2\,440\ (1 - X) \quad \text{(A.5)}$$

As a first approximation for LCVLOI a value of 23 000 kJ/kg LOI can be assumed.

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Annex B
(informative)

Various systems to input sludge into a household waste incineration plant

B.1 General

In order to complement this document, it is worthwhile pointing out some input systems. The list is not exhaustive and can be complemented at any time.

It can be divided into two major parts:

— the input of sludge whose DM content < 35 %;

— the input of sludge whose DM content > 65 %.

B.2 Sludge whose DM content < 35 %

There is a lot of feeding systems:

— through a crane (mixed waste);

— through a hopper;

— into the furnace, at various points;

— pipe;

— side wall or ceiling;

— output of post combustion;

— post combustion.

According to the systems, the sludge is:

— injected in form of "cakes";

— pulverised in form of drops;

— cut into slices.

B.3 Sludge whose dryness is > 65 %

There are several methods to input sludge into a furnace:

— sludge can be directly discharged from the pit into the drop chute through an air conveyor, a screw or bucket conveyor. The hopper is fed as regularly as possible in order to mix small quantities of household waste with sludge;

— sludge can be directly discharged into the furnace;

— sludge can be directly dumped into the household waste pit.

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B.4 Sludge whose DM content is between 35 % and 65 %

Storage and transfer technologies are not yet mastered for this kind of sludge.

B.5 Drying the sludge in the household waste incineration plant

Drying the sludge in the plant changes the sludge whose dryness is about 20 % into sludge of 60 % to 90 % dryness by using the energy recovered from household wastes. In this way, solid and incinerated sludge generate power.

Depending on the drying method, the sludge drying can generate a polluted liquid effluent that has been treated. Some problems can occur if drying is carried out an incineration plant limited in its liquid discharges.

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Annex C
(informative)

Case studies

C.1 Incineration

C.1.1 Pressurized fluidized bed incineration system

C.1.1.1 Background and results

Fluidized bed furnace (FBF) can combust sludge easily and completely, therefore is the most popular furnace for sewage sludge. However, the process has disadvantage of large power consumption because it requires huge capacity of fluidization fan to fluidize sand bed and induced draft fan for flue gas. In addition, a technology that can decrease production of N_2O which has been recently attracting attention as GHG is required. The pressurized fluidized bed incineration system located in Tokyo (Japan), deals with energy saving and global warming measuring. Its power consumption is 132 kWh/ton DS and the N_20 formation is 0,82 kgN_2O/ton-DS.

C.1.1.2 Description

Conventional FBFs are operated under minus pressure. On the other hand, the pressurized fluidized bed furnace is operated under plus pressure due to fluidizing air compressed by using turbo charger operating in flue gas pressure. Additionally, flue gas can be emitted without fan by its contained pressure. Therefore, fans which consume large power are not required and the whole system power consumption can be reduced to 40-60 % compared to FBFs. N_2O production can also decrease to ca.50 % compared to conventional FBFs because oxygen and organic matters reaction becomes active and high temperature zone, 900 C, is formed in the furnace.

The capacity is 300 tons/day for 1 train. The operation started in April 2014. The equipment is mainly composed of an incinerator (I.D 5,4 m × 11 mH, 850 °C to 900 °C), a sludge pump, an air preheater, a bag filter, a turbo charger, a scrubber and a stack (see Figure C.1).

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