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Unit Operation Model for the Thermal Treatment Channel

Acronym: AWAST

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*Material, economic, energetic and environmental modelling and simulation tools for the selection, evaluation and optimisation of a complete MSW chain***.**

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Name of the co-ordinator: Jacques Villeneuve
Project home page: http://awast.brgm.fr

Name of the authors:
Erling Næss – Energos(text)
Knut Sandvik – NTNU (appendix)
Jacques Villeneuve et al. – BRGM (appendix)
Roland Fehringer et al.– TU Wien (data for appendix)

Energy, Environment and Sustainable Development

Summary

This report is concerned with the formulation of the Thermal Treatment Plant (TTP) model within the AWAST project (**A**id in the Management and European Comparison of Municipal Solid **WAS**te **T**reatment Methods for a Global Sustainable Approach). The report considers the utility consumption, energy generation and material flow balance for the thermal treatment channel, and describes the different modules that defines the TTP.

The following Thermal Treatment Plant (TTP) combustion/incineration systems are considered:

- I: Grate Furnace systems
- II: Fluidized bed Furnace systems
- III: Cement Kiln Incineration systems

The grate furnace system is the most widespread of these with respect to Municipal Solid Waste (MSW) combustion, and may be found in a variety of technologies and sizes. Cement kilns are mainly used for the incineration of special waste fractions, where the trace pollutants (heavy metals, etc) and ash are bound to the solid phase product (cement).

These systems may be equipped with the following flue gas cleaning systems

- A: Dry cleaning (Applicable for type I TTPs)
- B: Wet scrubbing (Applicable for type I, II and III TTPs)

A third type of system, namely a semi-dry system is also commonly used. This is similar to the dry system, but here the reactant (hydrated lime) is mixed in a water slurry in order to increase the acid removal efficiency. In the context of this project, the difference between dry and semi-dry type of system is not considered significant in terms of efficiency or utility usage, and they are therefore treated similarly.

The thermal treatment plant is defined to consist of the following main components:

- i. Waste pre-treatment system (sorting, grinding etc.)
- ii. Furnace
- iii. Boiler
- iv. Flue gas cleaning system

It should be noted that the cement kiln systems do not normally contain a boiler system; the heat generated from the combustion process is normally used for product pre-heating and chemical binding during the cement production process.

The components are modeled with respect to:

a) Thermal energy generation and losses.
b) Mass flow analysis with respect to the selected elements C, N, S, Cl, F, P, Fe, Al, Pb, Zn, Cd, Hg.
c) Utility usage (water, air, electricity).

Regarding utility usage, a simplified global approach, considering the entire system/plant is used.

A number of constants and proportionality factors are introduced in this report. Where appropriate, numerical values have been indicated, but most of the constants depend on the type of TTP technology, and is therefore subject to empirical fitting and improvement as the database becomes more reliable. The numerical values of these constants are evaluated and reported elsewhere in the AWAST project.

The appendix shows a USIM PAC model of the Spitelau Incinerator in Vienna using as a starting point the model developed for the Orleans Incinerator. Some effort has been done so the model can use the transfer functions listed in work package 21, but to make the program capable of using the transfer functions consequently through the flowsheet, would require substantial reprogramming. A model for the "average" incinerator is therefore not yet available.

UNIT OPERATION MODEL FOR THE THERMAL TREATMENT CHANNEL

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1 OVERALL MODEL

The main model for the Thermal Treatment Plant is as sketched in Figure 1.

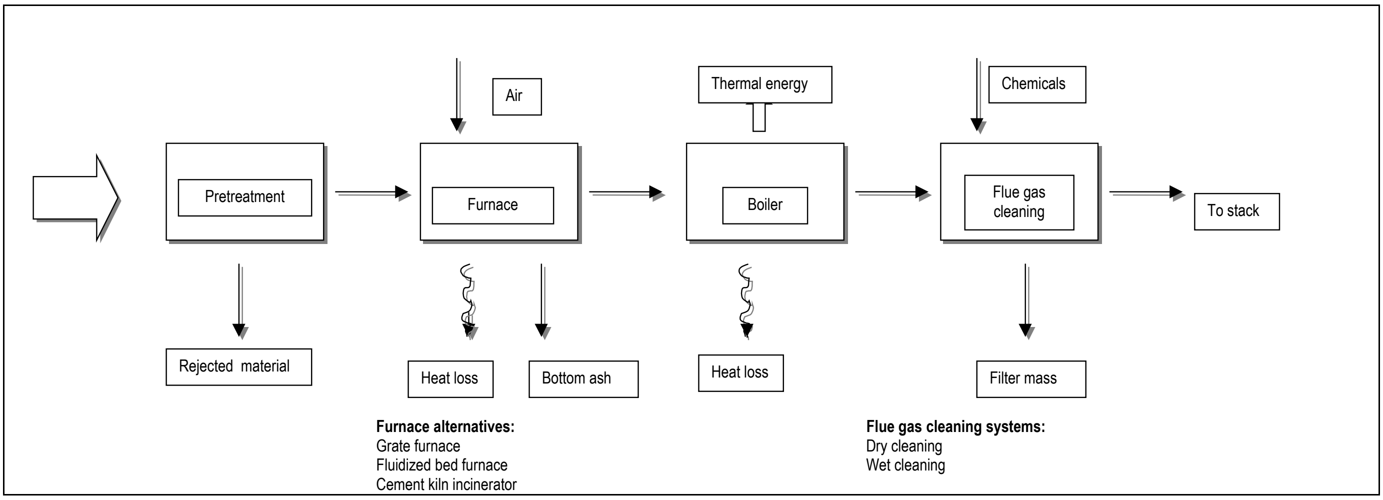

Figure 1 Overall model for Thermal Treatment Plant

The TTP is considered as a system built up of a series of unique modules. The modules considered are:

- Pre-treatment system, which principally serves as a waste grinding/ homogenization unit (required for cement kilns, fluidized beds and some grate systems). In addition, some waste components may be sorted out here. Note that this is NOT a waste fraction sorting facility.

- Furnace, where the waste is incinerated and heat is released. Combustion air is added to the process, and bottom ash is separated from the remaining flow. Three options are available as furnaces: Grate systems, fluidized bed systems and cement kilns.

- Boiler, where thermal energy is extracted from the flue gas. Output from the boiler module is thermal energy (in the form of saturated or superheated steam or hot water), and cooled flue gas (including fly ash). The thermal energy is transported out of the TTP boundary, and may be further utilized as process heat, electricity generation etc.

- Flue gas cleaning system, which may be dry cleaning or wet scrubbing systems. In this module fly ash is separated from the flue gas, and certain flue gas components (heavy metals, chlorine, sulphur) are partially removed from the flue gas by means of addition of chemical compounds (limestone, activated carbon etc). The *dry cleaning type* flue gas cleaning system are mainly applicable for small and medium-sized systems with less restrictive emission limits and/or systems with advanced primary measures technology (i.e. advanced combustion technology). The *wet scrubber* type is normally found in larger units.

Each of the modules and the modeling of the relevant processes are described in the following paragraphs.

2 MODELS RELATED TO THE THERMAL ENERGY TRANSFER

2.1 Incinerator

The function of the incinerator is to convert the chemically bound energy in the waste to thermal energy. In this process some mechanical energy is required (air/flue gas pumping, grate movement etc). Chemical energy is converted to thermal energy, and the waste is separated into several sub-fractions (flue gas, bottom ash, fly ash). In this section the sub-models for each incineration concept is described.

2.1.1 General: Combustion air requirement and flue gas generation

In order to fully oxidize the combustible components of the waste, the theoretical oxygen requirement for stoichiometric combustion (i.e. no oxygen content in the flue gas) is:

$$O_2^* = \frac{32}{12} \cdot C + 8 \cdot H + S - O \quad \text{[kg/kg waste]} \qquad \text{(i)}$$

Here, C, H and S are the combusted mass fractions of carbon, hydrogen and sulphur (on wet and ash-content basis) [See ch. 4.1 for a model yielding the combusted fraction]. O is the oxygen-content in the waste. H and O are currently not included in the "Waste Matrix", and must therefore be estimated. The index * refers to stoichiometric conditions

Dry atmospheric air is composed mainly of nitrogen (75.542%-w), oxygen (23.142%-w), argon (1.265%-w) and carbon dioxide (0.051%-w) [Witte (1994)]. For engineering purposes, however, satisfactory accuracy is obtained lumping all inert components into the nitrogen fraction, i.e. assuming atmospheric air to consist of only oxygen (23.14%-w) and nitrogen (76.86%-w). The stoichiometric air requirement may then be calculated as:

$$Air^* = \left(1 + \frac{76.86}{23.14}\right) \cdot O_2^* = 4.32 \cdot O_2^* \quad \text{[kg/kg waste]} \qquad \text{(ii)}$$

In order to ensure efficient combustion, all practical systems operate with oxygen excess in the combustion process, quantified by the excess oxygen (or excess air) ratio, λ:

$$\lambda = \frac{O_{2,Actual}}{O_2^*} \qquad \text{(iii)}$$

where $O_{2,Actual}$ [kg/kg waste] is the actual oxygen used, including the oxygen content in the fuel.

The actual air requirement is then

$Air = 4.32 \cdot \lambda \cdot O_2^* = 4.32 \cdot \lambda \cdot \left(\frac{32}{12} \cdot C + 8 \cdot H + S - O\right)$	[kg/kg waste]	Eq. 2-1

The total flue gas generated in the combustion is calculated (assuming dry combustion air and complete combustion) from:

$FlueGas = \frac{44}{12} \cdot C + 9 \cdot H + 2 \cdot S + N + 0.7686 \cdot Air + 0.2314 \cdot \frac{(\lambda - 1)}{\lambda} \cdot Air + M$	[kg/kg waste]	Eq. 2-2

The right-hand side terms represent the CO_2, H_2O and SO_2 generated by the combustion, the N_2 released from the waste, inert N_2 in the combustion air, the excess O_2 in the combustion air, and the evaporated moisture in the waste. It is assumed here that there is complete vaporization of the waste moisture. N is the waste mass fraction of nitrogen that is converted to gaseous phase (See ch.4.1). Note that H and O are not specified in the Waste Matrix, and must be estimated.

2.1.2 Net heating value

In the combustion process, chemical energy is converted to thermal energy. The net heat released is normally calculated assuming complete combustion. It is imperative that a unified approach is used in establishing the heating value. Using the present definition in the Waste Matrix of this project, the heating value is defined as the net (lower) heating value based on a moist, ash-containing fuel.

The net heating value is simply calculated as

$H_U = \sum_i X_i \cdot H_{U,i}$	[J/kg waste]	Eq. 2-3

Here, X_i is the mass fraction of waste fraction *i* (mixed waste, batteries, bulky waste etc. in the Waste Matrix), and $H_{U,i}$ is the corresponding heating value (also found in the Waste Matrix).

For cement kilns, some of the heat released may be consumed by endothermic reactions in the cement production. Also, cement kilns frequently make use of additional firing (oil burners, coal firing), complicating the energy conversion/mass balance calculations with respect to the waste fraction exclusively.

2.1.3 Thermal heat losses

Heat is lost from the furnace by means of wall heat losses (convection and radiation heat loss to the surroundings), and by active cooling of certain components, where the heat extracted is rejected to the atmosphere.

The heat losses by convection and thermal radiation from the furnace system to the surroundings may be established using empirical correlations and typical operating data, and is here considered in conjunction with the heat loss from the boiler system, described in Ch. 2.2.1. The remaining heat losses are mainly due to grate cooling and the heat content of the bottom ash fed out from the incinerator.

Grate cooling:
A simple model assuming a constant grate surface area per unit mass of waste yields:

$P_{grate} = C_{grate}$	[J/kg waste]	Eq. 2-4

where C_{Grate} is a constant depending on the type of furnace.

The specific heat loss from the bottom ash is proportional to the bottom ash content and -temperature:

$P_{BottomAsh} = X_{BottomAsh} \cdot Ash \cdot C_{BottomAsh} \cdot T_{BottomAsh}$	[J/kg waste]	Eq. 2-5

Here, *Ash* is the mass fraction of ash in the waste, $X_{BottomAsh}$ is the fraction of the ash that leaves the furnace as bottom ash (as opposed to fly ash). $C_{BottomAsh}$ is a constant depending on the furnace type. $T_{BottomAsh}$ is the temperature of the ash leaving the furnace, which also is furnace type dependent.

2.2 Boiler

2.2.1 Thermal heat duty

The main function of the boiler is to transfer the thermal energy from the hot flue gas and to a thermal carrier such as water or steam. The net heat transferred is calculated from:

$P_{Boiler} = H_U - \sum HeatLosses$	[J/kg waste]	Eq. 2-6

Here, the *HeatLosses* consist of

1. Heat loss by grate cooling, P_{Grate}, (Eq. 2-4)
2. Heat loss in bottom ash, $P_{BottomAsh}$ (Eq. 2-5)
3. Heat loss by convection/radiation from furnace, boiler and auxiliary components, $P_{RadiationLoss}$, (Eq. 2-7)
4. Heat losses due to regular boiler water conditioning (Eq. 2-8)
5. Heat loss in the flue gas leaving the boiler, $P_{FlueGasLoss}$ (Eq. 2-9)

The wall heat losses due to convection and radiation are dependent on the size (i.e. surface area) of the units, as well as the external surface temperatures. Size and surface temperatures are to some extent dependent on the generation (i.e. age) and technology type. However, the total heat losses may be estimated with sufficient accuracy using "rule-of-thumb" or empirical approaches. In the present study, the total convective/radiative heat loss from the combined furnace and boiler system is estimated using an empirical expression derived from Niessen (1995):

$P_{RadiationLoss} = C_1 \cdot \left(C_2 \cdot P_{des}\right)^n \cdot \exp\left(C_3 \cdot X\right) \cdot m_w^{-1}$	[J/kg waste]	Eq. 2-7

Here, C_1-C_3 are empirically determined constants depending on the furnace and boiler system, X is the fraction of the sidewalls that are water- or air-cooled, and n is an empirically determined constant. P_{des} is the design heat input/generation in the furnace ($=m_{w,des} \cdot Hu$ for furnaces without additional firing. $m_{w,des}$ is the design waste flow rate, H_u is the net calorific heating value (Eq. 2-4)). m_w is the actual waste feed rate. According to Niessen (1995), the following is proposed:

$C_1 =$ 4.276
$C_2 =$ 1.163
$C_3 =$ 0.0 (non-cooled furnace/no boiler)
$-1.3926 \cdot 10^{-3}$ (Air cooled sidewalls)
$-2.8768 \cdot 10^{-3}$ (Water-cooled sidewalls)
$n =$ 0.63

For modern systems with heat recovery, the furnace and boiler walls are water-cooled, hence $C_3 = -2.8768 \cdot 10^{-3}$, except for cement kilns, which have uncooled furnaces and little or no energy recovery (i.e. $C_3=0$). X may be typically be taken as 0.5 for modern systems.

A similar but somewhat simpler alternative expression is proposed in DIN 1942 (Heat Balance of Steam Generator), presented in Witte (1994):

$$P_{RadiationLoss} = C \cdot P_{des}^{\;0.7} \cdot m_w^{-1}$$

However, no numerical values for the constant C as a function of MSW incinerator or boiler technology were stated.

Note that the radiation/convection heat loss is constant, irrespective of the waste flow rate (i.e. specific heat loss is inversely proportional to waste mass flow rate).

Maintaining sufficient water quality in the boiler system requires flushing of polluted water from the steam drum at regular intervals. The flushed mass flow ($m_{BleedOff}$) is estimated in Eq. 3-10, and the specific energy content is $h_{l,sat}$, the enthalpy of saturated water at the boiler operating pressure. The water bleedoff heat loss is calculated from Eq. 2-8.

$P_{BleedOff} = m_{BleedOff} \cdot h_{l,sat}$	[J/kg waste]	Eq. 2-8

The flue gas heat loss represents the effective heat of the flue gas exiting the boiler. It is important to point out that this definition must correspond to the definition of H_U (Eq. 2.4). It is assumed here that no net flue gas heat is extracted after leaving the boiler. Hence, if a combustion air preheater is present, the boiler is defined <u>not</u> to include this unit. The flue gas heat loss is determined from:

$P_{FlueGasLoss} = FlueGas \cdot C_{FlueGas} \cdot T_{FlueGas,Boiler}$	[J/kg waste]	Eq. 2-9

Here, *FlueGas* is the specific flue gas mass flow rate (Eq. 2.3), $C_{FlueGas}$ is the mean effective flue gas specific heat capacity between the reference temperature for H_U (normally 20°C) and the flue gas temperature at the boiler exit ($T_{FlueGas,Boiler}$).

2.3 Waste pre-treatment and flue gas cleaning

Within the boundaries of the TTP, no thermal energy transfer takes place in these units. On a fundamental basis it may be argued that flue gas reheating after wet scrubbing should be considered. However, hot gas from the boiler exit is commonly used to reheat the cleaned, cold gas before the stack. Since the heat content of the boiler exit gas is considered lost anyway, no additional heat requirements are present when this gas is used to reheat the scrubbed gas.

3 UTILITY CONSUMPTION MODELS

3.1 Electricity

3.1.1 Waste pre-treatment system

The waste pre-treatment system may typically consist of a simple system where major components such as larger household appliances, car tires, TVs etc. are removed before being fed to the furnace. In addition, some Thermal Treatment Plants require homogenization/grinding of the waste before incineration, e.g. Fluidized Beds and some grate systems.

3.1.2 Waste separation/sorting

Normally, waste separation takes place in separate processing units, where recyclable, hazardous and other waste fractions are separated. For the TTP channel it is therefore assumed that proper waste separation is performed prior to entering the TTP, and that no additional material separation is required. Waste separation is described within the framework of collection, transport and sorting of waste in a separate deliverable (as a part of WP 4).

3.1.3 Grinding or shredding

For incinerators requiring waste homogenization, grinding or shredding of the waste prior to combustion is necessary. Typical applications are Fluidized Beds and some grate systems. Grinding/shredding does not influence the waste composition and does not split the flow; it is merely an operation that requires mechanical energy in order to homogenize the waste.

Grinding and shredding are operations that typically require mechanical energy (in the form of motors). The energy source may be electricity, steam (using a steam engine or turbine) etc.

Based upon empirical experience, the specific energy consumption (work units per unit waste) depends upon the size to which the waste is crushed/ ground. The specific energy consumption is roughly proportional to the weighted average product particle size D to the power of -0.9 (i.e. 63.2% of the waste mass has less effective particle diameter than D) [Niessen (1995)] for horizontal shaft shredders. Due to lack of available data, no attempt is made here to differentiate the requirements in D for the various technologies (grate technologies, Fluidized Beds etc). Hence, the specific work required is assumed constant and may therefore be expressed as:

$W_I = C_{I,1}$	[W·s/kg waste]	Eq. 3-1

The constant $C_{I,1}$ is normally dependent on the waste composition and the shredding method used; however, it is anticipated that the overall variability due to the shredding method or waste composition is minor compared to the level of many other energy consuming processes in the TTP.

3.1.4 Furnace

The main energy consumer is the combustion air and flue gas pumping. These are treated in Ch. 3.1.6.
The other mechanical energy requirements (grate movement etc) are considered minor, and are not treated separately, but rather lumped into a "miscellaneous" consumption term, see ch. 3.1.8.

3.1.5 Boiler

The main electric power consuming process is the operation of the feed water and evaporator circulation pumps. Evaporator recirculation pumps are only used in forced circulation type boilers. The specific power consumption may be expressed as

i. Feed water pumps

$W_F = \frac{Q \cdot \Delta p_F}{\eta}$	[W·s/kg waste]	Eq. 3-2

ii. Circulation pumps

$W_S = \frac{n \cdot Q \cdot \Delta p_S}{\eta}$	[W·s/kg waste]	Eq. 3-3

Here, η is the overall pump and motor efficiency (approximately 0.75), Q is the specific steam production rate (or specific water throughput for hot-water units), which may be calculated from the expression

$$Q = \frac{1}{\rho_w}\left(\frac{P_{Boiler}}{\left(h_{out} - h_{in}\right)} + m_{BleedOff}\right) \qquad [\mathrm{m^3/kg\ waste}]$$

where P_{Boiler} is the boiler duty (Eq. 2-6), ρ_w is the liquid water density at the pump condition (approximately 1 bar and 100°C), and $(h_{out}-h_{in})$ is the enthalpy change for the water/steam in the boiler system. $m_{BleedOff}$ is the water-consumption in the boiler system, see Eq. 3-10. Δp_F and Δp_S are the pressure increases in the pumps, tentatively Δp_F=Boiler Operation pressure + $3 \cdot 10^5$ Pa, $\Delta p_S = 3 \cdot 10^5$ Pa. n is the circulation ratio, typically in the range 5-10.

3.1.6 Combustion air and flue gas pumping

Mechanical (or electrical) work required for the TTP consist mainly of the operation of the

- combustion air,
- flue gas and
- flue gas recirculation

fans. The pumping power is proportional to the gas flow rates and the pressure drops, which are largely technology dependent. The general models for the pumping required are thus

i. Combustion air

$W_A = \dfrac{Air \cdot \Delta p_{Air}}{\rho_{Air} \cdot \eta}$	[W·s/kg waste]	Eq. 3-4

ii. Flue gas to stack

$W_A = \dfrac{FlueGas \cdot \Delta p_{Fluegas}}{\rho_{Fluegas} \cdot \eta}$	[W·s/kg waste]	Eq. 3-5

iii. Flue gas recirculation

$W_A = \dfrac{X \cdot FlueGas \cdot \Delta p_{\mathrm{Recirc}}}{\rho_{Fluegas} \cdot \eta}$	[W·s/kg waste]	Eq. 3-6

Here, *Air* is the air flow rate (Eq. 2-1), *FlueGas* is the generated flue gas flow rate (Eq. 2-2), Δp_{Air}, $\Delta p_{Fluegas}$ and Δp_{Recirc} are the pressure increases for the respective fans (being technology specific), ρ_{Air} and $\rho_{Fluegas}$ are the gas densities at the fan inlets, and η is the total combined efficiency of the fan, gear and motor. X is the recirculation ratio of the flue gas. Some typical values are ρ_{Air}=1.2 kg/m^3, $\rho_{Fluegas}$= 0.95 kg/m^3, η=0.75, X=0.4-1.0.

Sometimes the flue gas and recirculated flue gas flows are combined into one fan. This does not change the calculation methodology; it merely means that $\Delta p_{Fluegas}$ and Δp_{Recirc} are equal.

3.1.7 Ventilation

Ventilation is required in the furnace/boiler room in order to remove the heat lost from the TTP components. The calculation procedure is similar to those of the preceding paragraph. The heat that needs to be removed is, however, proportional to $P_{RadiationLoss}$ (Eq. 2-7), and a simple model is then to assume a linear relation:

$W_V = C \cdot P_{RadiationLoss}$	[W·s/kg waste]	Eq. 3-7

where C is a proportionality constant.

3.1.8 Miscellaneous

There are obviously other minor energy consumers in a TTP plant. These may be attributed to control systems operation, utility systems, lighting, boiler cleaning, personnel room heating and ventilation etc. It is not practicable to include all these contributions as separate models. A more simplistic model is proposed:

$W_{Misc} = C_1 + C_2 / m_W$	[W·s/kg waste]	Eq. 3-8

where C_1, C_2 are proportionality constants and m_w is the waste flow rate.

3.2 Water consumption

3.2.1 Furnace

In the furnace, only minor amounts of water are consumed. The principal consumption point is arguably the bottom ash cooling pit, where bottom ash is cooled from furnace temperature and down to a temperature of 40-60°C by evaporation of water. In addition, some of the cooling pit water is transported out of the system as remaining moisture in the cooled bottom ash. Considering only these contributions, the water consumption in the furnace may be estimated as

$$m_{w,furnace} = \frac{P_{BottomAsh}}{h_s - h_l} + X_{BottomAsh} \cdot Ash \cdot \varphi$$

Here $P_{BottomAsh}$ is the sensible heat in the bottom ash leaving the furnace (Eq. 2-5), Δh_l is the enthalpy change of the water (from 20°C to saturated vapor at 1 bar pressure), $X_{BottomAsh}$ is the bottom ash fraction of the total ash content Ash, and φ is the moisture fraction of the moisturized, cooled bottom ash, typically in the range of 1.0. Introducing numerical values, the expression becomes

$m_{w,furnace} = \frac{P_{BottomAsh}}{2591 \cdot 10^3} + X_{BottomAsh} \cdot Ash$	[kg/kg waste]	Eq. 3-9

3.2.2 Boiler

During boiler system operation, impurities such as salts, corrosion products etc. accumulate in the evaporator section and in the steam drum. These must be removed at regular intervals, and boiler water is bled from the system at regular intervals. The amount of boiler water bled depends on the boiler technology, the quality and treatment of the boiler feed water, the condition of the overall steam and return condensate system, the ratio of freshwater makeup to condensate return flow rate, to name but a few parameters. Available data for boiler water bleed-off are too scattered in order to establish any general correlation or rule-of-thumb. Therefore, a simple model assuming proper boiler-water treatment is proposed. Typical values for the electrical conductivity in the feed water (S_f) and boiler drum (S_d) are assumed, and a model for the required bleed-off rate is calculated based on these values only. The boiler water bleed-off rate ($m_{BleedOff}$) is calculated from a electrical conductivity "balance", assuming that the electrical conductivity of the steam exiting the boiler is zero:

$$m_{BleedOff} = Steam \cdot \frac{S_f}{S_d}$$

where *Steam* is the specific steam production rate, given as

$$Steam = \frac{P_{Boiler}}{h_{out} - h_{in}}$$

here, P_{Boiler} is the specific boiler duty (Eq. 2-6), h_{in} and h_{out} are the boiler water inlet and steam outlet enthalpies, respectively. Combining these, the bleed-off rate becomes

$m_{BleedOff} = \frac{P_{Boiler}}{h_{out} - h_{in}} \cdot \frac{S_f}{S_d}$	[kg/kg waste]	Eq. 3-10

Values for S_f and S_d depend on a number of plant parameters. In lack of plant specific data, typical values of S_f =15 µS/cm and S_d=1000 µS/cm may be used.

3.2.3 Flue gas cleaning system

3.2.3.1 Dry and semi-dry systems

Water is often injected to the flue gas in order to bring the temperature down to approximately 150°C. Low flue gas temperature increases the calcium hydroxide adsorptivity of chlorine; however the temperature should not be reduced to a level where products (i.e. $CaCl_2$) becomes strongly hygroscopic and possibly wet. The water consumption associated with bringing the flue gas temperature down to the desired temperature of approximately 150°C is then approximately:

$m_{water} = \frac{FlueGas \cdot 1200 \cdot (T_{Exit,Boiler} - 150)}{2.684 \cdot 10^6}$	[kg/kg waste]	Eq. 3-11

Here, *FlueGas* is the amount of flue gas per unit waste mass (see Eq. 2-2) and $T_{Exit,Boiler}$ is the flue gas temperature at the boiler outlet (in °C). Eq. 3-11 is valid both for dry and semi-dry systems.

3.2.3.2 Wet scrubber systems

Wet flue gas cleaning systems (wet scrubbers) normally consist of a primary scrubber for removal of chlorine and mercury, followed by a secondary scrubber for sulphur removal. The primary scrubber often use only water, whereas the second unit use additives in the form of NaOH, or more commonly $CaCO_3$ (or sometimes $Ca(OH)_2$).

The water consumption may be roughly estimated assuming that the flue gas is cooled to T_{lo} where it will be saturated with water vapor.

The water consumption thus becomes:

$$m_{water} = \frac{p_{SAT}(T_{lo})}{p} \cdot \frac{MW_{H_2O}}{MW_{FLuegas}} \cdot FlueGas - \left(9 \cdot H + M\right)$$

Here, $p_{SAT}(Tlo)$ is the saturation pressure of water vapor at temperature T_{lo}, p is the system pressure, MW_{H2O} and $MW_{Fluegas}$ are the molecular masses for water and flue gas, respectively, *FlueGas* is the flue gas flow rate (Eq. 2-2), *H* and *M* are the hydrogen and moisture fractions in the waste. The second term on the right-hand-side represents the moisture content in the flue gas entering the wet scrubber system.

Assuming that the flue gas is cooled to 60°C, and assuming a flue gas molecular mass $MW_{Fluegas}$ = 27 kg/kmol, the expression is simplified to

$m_{water} \approx 0.133 \cdot FlueGas - (9 \cdot H + M)$	[kg/kg waste]	Eq. 3-12

3.3 Other utility usage

In this paragraph, the use of chemical additives in the flue gas cleaning system is considered.

3.3.1 Dry and semi-dry systems

Dry cleaning systems normally utilize lime (in this report taken as calcium hydroxide – $Ca(OH)_2$) to capture acidic components (chlorine and sulphur), and activated carbon to capture heavy metals and dioxin. Normally, the calcium hydroxide and activated carbon are premixed (as opposed to separate dosing); the premix ratio may vary depending on the waste and combustion technology.

A simple model for the $Ca(OH)_2$ consumption may taken as the sum of the sulphur and chlorine adsorption requirements, being proportional to the sulphur and chlorine concentrations in the uncleaned gas. The remaining Cl and S content in the cleaned gas is very small, and may be ignored in the estimation of the $Ca(OH)_2$ requirement. The simple, linear model is then

$$m_{Limestone} = \left[\frac{X_{Cl}}{2} \cdot \frac{MW_{Ca(OH)_2}}{MW_{Cl}} + X_S \cdot \frac{MW_{Ca(OH)_2}}{MW_S} \right] \cdot \frac{1}{C}$$

where $m_{Limestone}$ is the required $Ca(OH)_2$ mass per unit waste, X_{Cl} and X_S are the mass fractions of chlorine and sulphur in the flue gas cfr. Eq. 4-1, and MW_{Cl}, MW_S, $MW_{Ca(OH)2}$ are the molecular masses for chlorine, sulphur and calcium hydroxide, respectively. C is an empirical constant representing the saturation ratio of the limestone. Inserting for the molecular masses, the equation may be rewritten as

$m_{Limestone} = [1.045 \cdot X_{Cl} + 2.31 \cdot X_S] \cdot \frac{1}{C}$	[kg/kg waste]	Eq. 3-13

The saturation ratio C is typically in the range 1.5 – 2 for dry systems, and 1.05-1.25 for semi.-dry systems (Christiansen (1998)).

3.3.2 Wet scrubber systems

The neutralization treatment of the scrubber fluid is complex, and involves a variety of additives (NAOH, H_2S, Na_2S, FeCl etc). The variety of additives and their consumption is technology specific, and no attempt is made at this stage to produce generalized models for the additive consumption. As a first approximation, the same model as for the dry system may be applied (i.e. Eq. 3-13), however with a saturation ratio C close to unity.

4 MASS FLOW ANALYSIS

4.1 Furnace

In the furnace, the waste is separated into gaseous fractions and solid ash. The major portion of the ash is fed out from the furnace as bottom ash; the remaining fraction is transported with the flue gas through the boiler and to the filter system. In fluidized beds and cement kilns additives may or may not be introduced in the furnace in order to bind sulphur and alkali metals to the bottom ash (or product). However, in this study, the use of such additives is disregarded.

For the non-metallic elements (C, N, S, Cl, F and P), the major fraction is transported out in the flue gas stream. However, small fractions may be bound in the ash and is fed out from the furnace in the bottom ash stream. A simple transfer coefficient is used to describe the elemental flow in the flue gas and bottom ash streams:

$X_{i,FlueGas} = C_i \cdot X_{i,Waste}$	[kg/kg waste]	Eq. 4-1
$X_{i,BottomAsh} = (1 - C_i) \cdot X_{i,Waste}$	[kg/kg waste]	Eq. 4-2

Here, $X_{i,Waste}$ is the concentration of element *i* (C, N, S etc) in the waste [kg/kg waste], C_i is the fraction of element *i* that follows the flue gas stream (as gas and fly ash). $X_{i,FlueGas}$ and $X_{i,BottomAsh}$ are the mass flows of element *i* in the flue gas (including fly ash) and bottom ash streams, respectively.

Regarding the metallic elements (Al, Pb, Zn, Cd, Hg), the situation is, at least in principle, more complex. Larger lumps of metal will normally behave as inerts and will be transported out with the bottom ash. Thus, the transfer coefficients should also reflect the distribution state of these elements. However, for the present, the same model (i.e. Eq. 4-1 and Eq. 4-2) is proposed also for the metallic elements.

4.2 Flue gas cleaning system

For the emission-controlled elements (S, Cl, F, P, Pb, Zn, Cd, Hg), the emissions to the atmosphere will be at or below the allowable emission-limits. For modern plants it is anticipated that there is ample margin with respect to these limits. A simple, but practical model describing the element flow split in the flue gas cleaning system is to assume that the emission to air is (on average) a fraction of the allowable limit:

$X_{i,Stack} = C_i \cdot EmissionLimit_i \cdot FlueGas$	[kg/kg waste]	Eq. 4-3
$X_{i,Filter} = X_{i,FlueGas} - X_{i,Stack}$	[kg/kg waste]	Eq. 4-4

Here, $X_{i,Stack}$ is the is the concentration of element *i* in the flue gas leaving the system, $X_{i,Filter}$ is the concentration of element *i* that is separated from the flue gas in the flue gas cleaning/filter system. $EmissionLimit_i$ is the maximum allowed concentration in the flue gas (specified per unit flue gas volume), and FlueGas is the specific flue gas flow rate [kg flue gas/kg waste], see Eq. 2-2. C_i is an empirically determined constant (in the range 0-1).

For non-emission controlled elements the following is used:

$X_{i,Stack} = C_i \cdot X_{i,FlueGas}$	[kg/kg waste]	Eq. 4-5
$X_{i,Filter} = X_{i,FlueGas} - X_{i,Stack}$	[kg/kg waste]	Eq. 4-6

Here, C_i are empirically determined constants.

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