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Investigation of Process Optimization Measures in MSWI Plants with an Online-Balancing Program

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1 Abstract

In Germany municipal solid waste is treated in more than 60 incineration plants (MSWI plants) with an overall capacity of over 16 Mio. tons per year. According to the further improvement of thermal waste treatment a lot of operational measures are under development with regard to the reduction of pollutant emissions, the improvement of ash quality, the increase of efficiency, the reduction of corrosion etc. These measures have still a high optimization potential.

For the investigation of the efficiency of different optimization measures detailed information about operational behaviour, related to the actual operating conditions are necessary. There for an online-balancing program has been developed describing the actual state of MSWI plants with detailed balances (material, mass and energy balances) for the different process units of the plant within main thermal process (incineration process), water steam cycle, flue gas treatment, energy conversion, treatment of residues etc. by using data from process control system. The online calculation of specific ratios and efficiencies for the different units (e.g. additive consumption in flue gas treatment, thermal and electric efficiency ratios) and also referring to the overall process (e.g. net plant efficiency) is possible.

Applied to different Bavarian municipal solid waste incineration plants the online-balancing program is numerically validated and with the investigation of chosen operational conditions concerning process optimization practically tested. There the online-balancing program the operational staff is able to optimize the overall process recording to the actual process conditions.

In the proposed paper first of all the balancing method as the basic of the online-balancing program will be explained. Next to the basics examples from practical validation of the program in MSWI-plants are presented and potentials for process optimization concerning the increase of energy efficiency are discussed.

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2 Introduction

The optimization of municipal solid waste incineration plants (MSWI) requires detailed information and data about the actual operating conditions. This information can be obtained from the plant's existing process control system. Modern process control systems utilize computers to collect and store process data as well as to control the actual process conditions. These control systems can report the actual measured process values in the plant as well as the time behaviour of these values. Process data includes air and flue gas flow rates, flue gas component concentrations (CO_2, CO, O_2, N_2, H_2O, etc.), mass rate of steam generated as well as steam temperature and pressure. In the newer MSWI plants the process control systems can provide sufficient information to allow mass and energy balances to be modelled for each of the process units and consequently for the overall process.

The following information is of special interest for optimization of MSWI plants:

- Mass flow (kg/hr), composition (weight percent) and calorific value (kJ/kg) of the waste and fuels fired in the combustion process
- Flow rates of combustion air and estimated infiltration air into the combustion systems
- Air flow rates used in the flue gas treatment system (compressed air, pulse air, or air used to convey solids)
- Combustion air preheating temperatures
- Total, electric and thermal efficiency ratios for the overall process
- Boiler and turbine efficiency
- Heat needed for condensate and feed water preheating, etc.

With this data the operational staff would have sufficient information to perform real time process optimization calculations and to implement process modifications of plant operations in order to increase the system efficiencies. Furthermore, it is envisioned that some of the manual process changes could be programmed into the existing control system to automate the optimization process.

Existing MSWI plants are not equipped with possibilities to model mass and energy balances "online". However, with such a tool of Online-Balancing[2] operational staffs are able to manually adjust the operational parameters in order to optimize the overall process.

Examples of opportunities for manual optimization include:

- Increase of overall energy efficiency of the system
- Reduction in reagents and additives used in the flue gas treatment system
- Increase availability of the system (decreased downtime)

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[2] In the following the real time calculation of mass and energy will be termed as Online-Balancing. The computer model applied for these calculations will be termed as Online-Balancing program.

- Reduced operating costs.

Therefore the Online-Balancing program displays to the user both the actual as well as the calculated operational data from detailed mass, material and energy balances in all essential process units and associated.

The Online-Balancing program was developed at the Schwandorf, Burgkirchen and Coburg MSWI plants in a project called "EU 24 – Effectiveness of Waste Incineration Plants; Technical, Ecological and Economic Optimization" [1]. This project was a collaboration of various companies and personnel including the three MSWI plants in Schwandorf, Burgkirchen and Coburg and Martin GmbH für Energie- und Umwelttechnik München (a plant engineering/construction company in Munich). The project was supported by the State of Bavaria Department of Health, Environment and Consumer Protection as part of an EU infrastructure funding for regional development (EFRE) program.

3 Basic Principles of Balancing

As is usual in process engineering, implementing a model for mass, material and energy balances for an MSWI plant first requires that the boundaries be established for each unit operation (for aggregates, apparatuses, etc. [2]) in the MSWI plant process. Figure 1 shows a schematic of a typical MSWI plant with the main input streams being the waste, air, energy, water and operation material, and the main output streams being the flue gas, residues, energy for utilization and (heat) losses. Single unit operations can be combined to form the paramount balance units which in this paper will be termed as (calculation) modules, for example for the bunker, firing, boiler, scrubber, etc. The combination of modules leads to single process units and the paramount process subdivisions such as the main thermal process (incineration process), energy conversion system, flue gas treatment system, etc. (Figure 1).

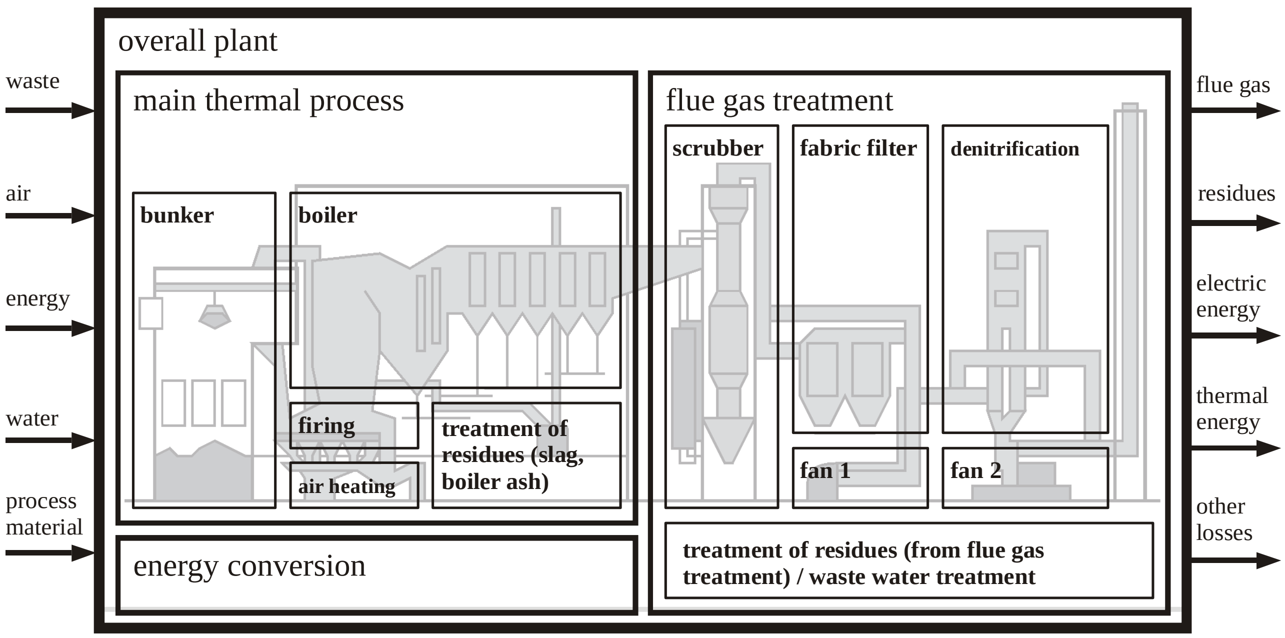

Figure 1. Balance modules for modelling a typical MSWI plant.

Once the boundaries of each module were defined the next process engineering step is to define the mass, material and energy balances for each of the calculation modules taking into consideration each of the input and output streams. Simply stated, the sum of all input mass and energy streams to a module must equal the sum of all output mass and energy streams from the module.

Some streams are difficult if not impossible to measure in real time and as such these streams will require an alternative calculation strategy. For example, the mass flow and composition of the actual solid waste feed to the incinerator is difficult to measure. This is calculated backward by the Online-Balancing program within the calculation modules "air preheating", "firing" and "boiler" from the measured values within the subdivision process "flue gas treatment". The calculation strategy therefore is shown in Figure 2.

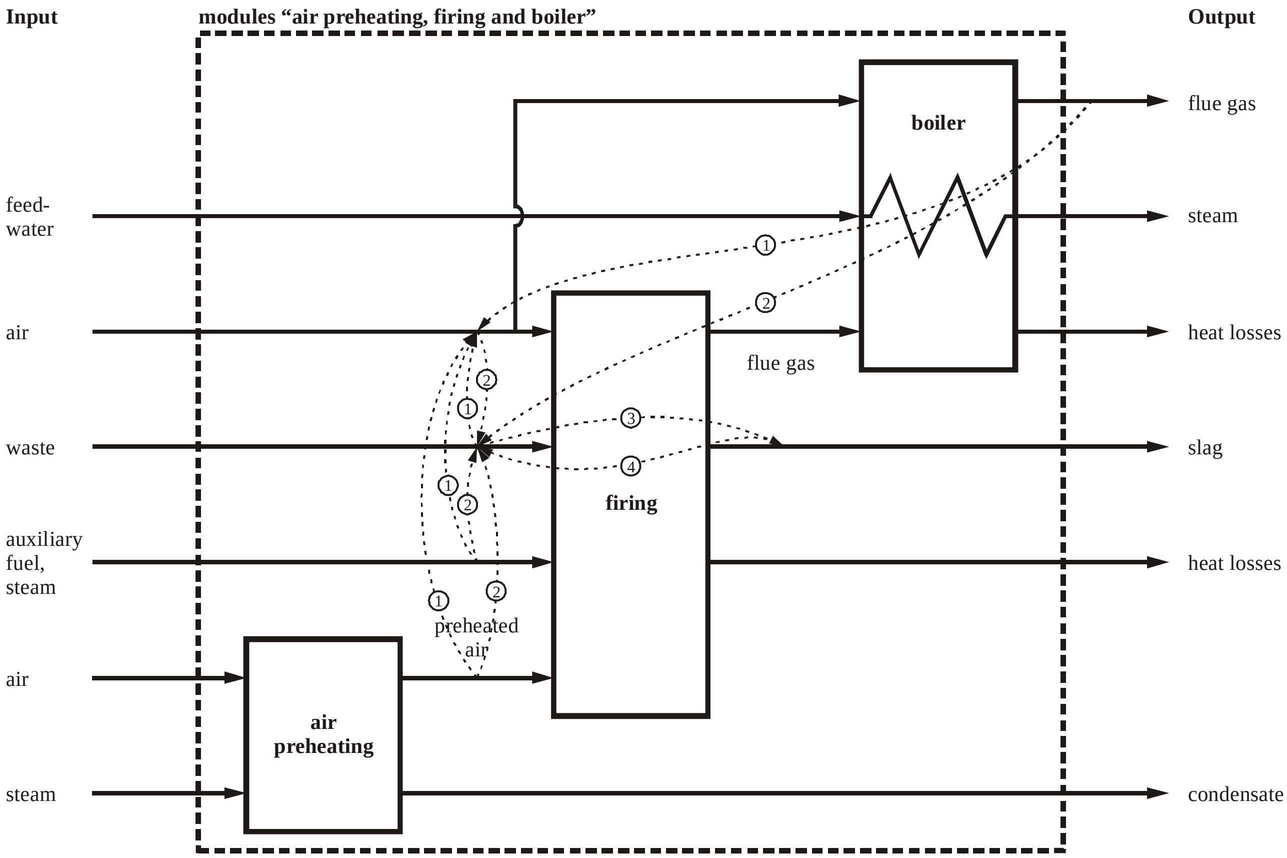

Figure 2. Modules "air preheating", "firing" and "boiler" in the MSWI-plant Schwandorf – Calculation strategy for mass flow and composition of waste (within step 1 to 4, illustration of important mass and energy streams).

The Online-Balancing program was designed to be modular with certain predefined calculation modules in a user accessible library (Figure 3). For each calculation module defining mass-, material- and energy balances is necessary. The user can create additional modules through an easy to use interface. Predefined calculation modules for firing, air preheating and turbines were developed during the implementation of the Schwandorf, Burgkirchen and Coburg MSWI plant project. With combination of different predefined or new defined calculation modules manually on the user interface (usually Excel spreadsheet) complex models of the different process units arise, leading to models of the single process subdivisions and after all to a model of the overall plant. Due to the application of an easy-to-learn user interface the configuration and adaptation of the program for other plants can be achieved quickly.

In modern MSWI plants the connection of the Online-Balancing program can be realized directly via a dedicated OPC-Server[3] or measuring value databases. Where possible, the program uses measured data when performing the heat and mass balance real time calculations. This measured data is imported into the program and validated before use in the model as follows:

1) Reads and records the measured data from process transmitters via the OPC-Server or database,

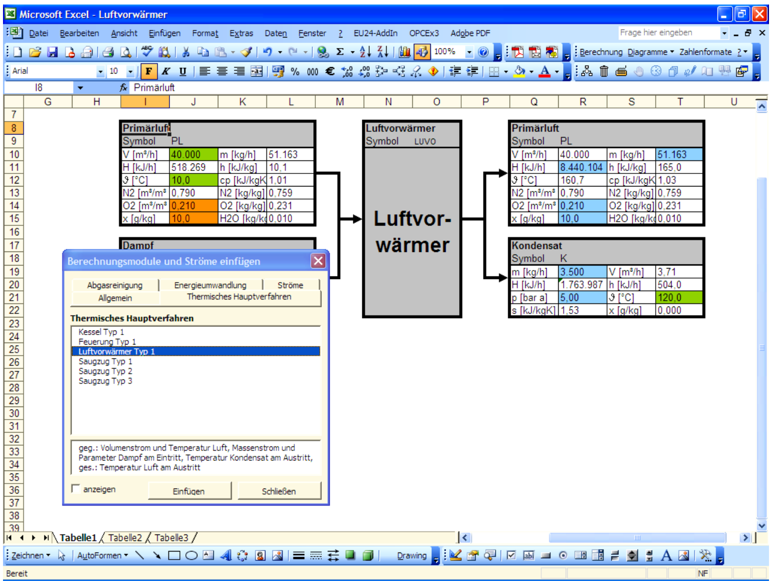

Figure 3. Implementing the calculation module "air preheating" ("Luftvorwärmer") from existing module library into the program.

2) Converts the measured digital or analogue signals and correcting the values to the calibration of the measuring device (if necessary),

3) Checks that the measured value is valid and the transmitter is not in a failed state. This is accomplished by checking if the value is within an individually defined ratio (upper and lower limit) and

4) Checks that primary operational parameters are at steady state (The model can be used to verify that the MSWI plant primary operational parameters are at steady state in accordance with German guideline VDI 3986 [3], [4]).

Furthermore, the measured values can be checked that they do not contradict with other (in over determined balancing equations) measured data and – when indicated – these data can be mathematically corrected within the model [5].

The Online-Balancing program uses, in addition to the measured values, stream data that can not be measured in real time and as such must be estimated and entered into the program by the user. These estimated values (in the program termed as parameters) must be checked to determine their potential impact on the results from the real time calculations. An example showing the impact a deviation from the actual conditions of the estimated ash content and atmospheric humidity on the calculation of the waste mass flow rate is shown in Figure 4. The graph in Fig. 4 indicates the following:

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3 OPC...OLE (Object Linking and Embedding) for Process Control. An OPC-Server is a hardware device driver enabling OPC capable standard software (OPC-Clients) to communicate with external devices without additional programming work.

- High deviations from actual conditions in the estimated atmospheric humidity has a relatively minor impact on the calculated mass flow of waste – at a 25% deviation in humidity the mass flow of waste is only impacted by approximately 2%.
- High deviations from actual conditions in the estimated ash content also has a minor impact on the calculated waste feed – at a 25 % deviation in ash content the mass flow of waste is only impacted by 8 %.

This analysis shows that it is unnecessary to continuously (real time) measure the atmospheric humidity and ash content in order to achieve good for the waste mass flow rate.

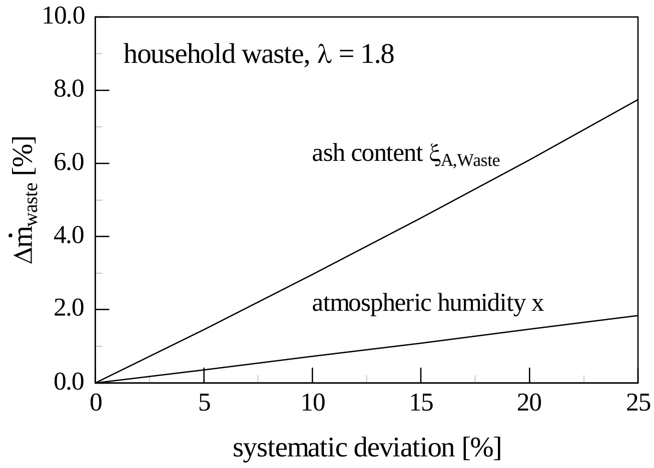

Figure 4. Propagation of uncertainties of measurement applied on the calculation of mass flow of (household) waste – influence of deviation in estimated ash content and atmospheric humidity.

In some modules the equations used in the model will not balance because the model is over determined with more (measured and estimated) values than required. In these processes it is possible to apply mathematical methods like the "Gaussian correction principle" [5] to detect and remove systematic measured deviations. In power stations such over determination is often seen in the water steam cycle which results from the high number of measuring points needed for efficient control and for regulatory compliance [6]. Another example is this effect can be seen during the start up of the MSWI plant. Over determination can occur while starting up the MSWI boiler since the fuel oil flow rate is measured and the estimates of the composition and heating values for the fuel oil are relatively accurate and constant. The fuel oil data is also calculated by the Online-Balancing program based on measured information from the balancing of subdivision process "flue gas treatment" as described previously (Figure 2). When the calculated fuel oil flow rate is compared to the measured flow rate it is very likely that there will be a deviation. Table 1 shows for a typical process condition the detected measuring values with systematic deviations and the corrections for removing the deviations based on an assumed confidence interval. In MSWI plants today this is usually not possible because the data recording systems are generally not equipped with the required

after boiler			after fan 1		
measuring value X	confidence interval $V_{X,95\%}$	calculated correction ΔX	measuring value X	confidence interval $V_{X,95\%}$	calculated correction ΔX
$\psi_{O2,AG,tr}$	0.2	+ 3.96	$\psi_{CO2,AG,tr}$	0.15	- 0.02
$\psi_{H2O,AG,f}$	0.2	+ 0.93	$\psi_{O2,AG,tr}$	0.2	+ 2.75
x	25	- 18.66			

Table 1. Measuring values with systematic deviations detected by applying error propagation and correction principles, all data in [%], explanation in text.

internal validity checks. It is obvious from this that the Online-Balancing program has application for the real time validation of measured values. For example variances between the actual and calculated data can be tracked and alarmed when key process parameters diverse significantly.

4 Investigation of Process Control Measures

One key process parameter is the calorific value of the waste which is of special interest for the process control in MSWI plants. Measuring the caloric value of the waste in real time is impossible at this time. However, this value can be real time calculated within Online-Balancing Program with relatively high certainty by performing an energy balance of the boiler and/or by using regression formulas based on the calculated composition of waste. Variations in calorific value obviously impact the efficiency ratio of the boiler and overall plant efficiency ([2], [7]) but it also impacts the feed rate of waste to the system. In the following example of the MSWI plant in Schwandorf (Figure 5) the factors that have the greatest impact on energy efficiency and throughput of the system are discussed.

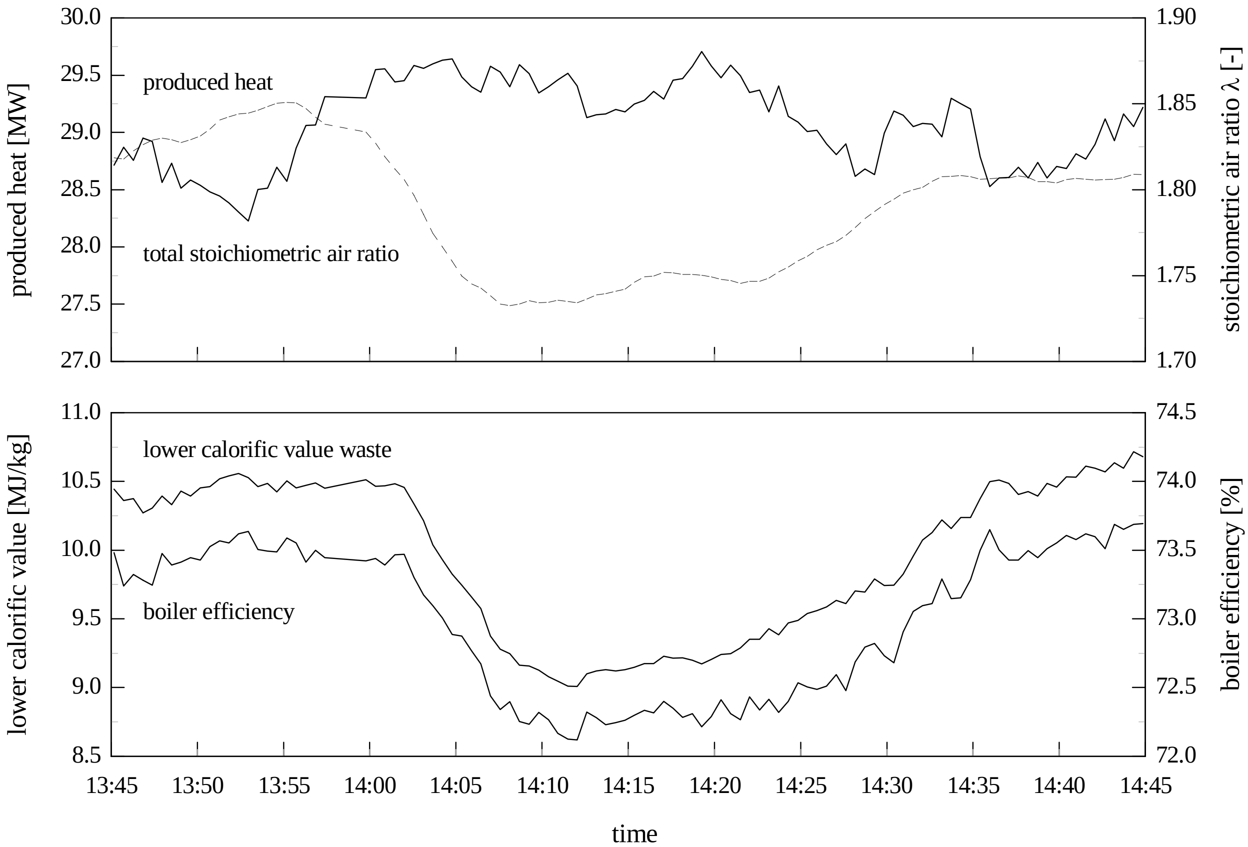

Figure 5. Lower calorific value of waste, boiler efficiency, total stoichiometric air ratio and produced heat (steam and water from grate cooling).

Figure 5 shows the rapid decrease in calorific heating value from approximately $h_{u,1}$ = 10.5 MJ/kg (in the following termed as state "1", 14:00 hours) down to $h_{u,2}$ = 9.0 MJ/kg (state "2", 14:12 hours). The produced heat (approximately 98 % steam and 2 % water from grate cooling) decreased in the same time period from over 29 MW down to 27.5 MW. The boiler efficiency ratio decreased in approximately 1.5 percent. The reason for the decrease in efficiency ratio is due to an increase in energy exiting the boiler with the flue gas since there was a corresponding increase in specific flue gas flow rate at this time (and therewith specific higher losses, related to the incoming energy). Also the ratio of mass flow rates in state "1" and "2" $\dot{m}_2 / \dot{m}_1$ increased over proportional compared to the ratio of lower calorific values $h_{u,1} / h_{u,2}$ (for $h_{u,1} > h_{u,2}$). The throughput in state "2" is 15 % higher then in state "1".

The overall plant has lower energy efficiency due to the low waste heating values and the higher flue gas flow rate. The higher flue gas flow rate results in increased energy consumption by the exhaust fans and the higher energy consumption for reheating the flue gas before the denitrification plant (Figure 1).

In addition to the waste and auxiliary fuel there are a number of other streams entering the plant (condensate from steam supply, water from district heating, reagents, etc.). When assumed that these other streams have negligible enthalpies compared to the relatively large enthalpy of the waste. The net plant efficiency ratio for the MSWI plant is approximately $\Delta\eta_{A,Netto} \approx -0.2\%$ [4]. This small influence of fluctuation in calorific value on the overall efficiency is caused by an almost constant total stoichiometric air ratio $1.8 \leq \lambda_{Total} \leq 1.9$ in the firing (Figure 5) which results in almost similar specific flue gas volumes ($v_1 \approx v_2$). This results from the mode of combustion control in the incinerators (incineration lines 1 to 3) of the MSWI plant in Schwandorf, where the volume flow of primary combustion air remains constant and the combustion control system regulates the mass flow of waste based on maintaining an oxygen concentration in flue gas after the boiler. The possible affect of integrating the calculated calorific value of

state		**"1"**	**"2"**	**"2a"**	**"2b"**	**"2c"**
		operational states		„optimized" states		
$h_{u,Balance}$	MJ/kg	9.0	10.5	10.5		
$\dot{Q}_{Boiler}$	MW	27.4	28.8	28.8		
$\dot{m}_{Waste}$	t/h	13.7	12.1	11.7	11.9	12.0
λ_{Total}	-	1.85	1.85	1.50		
λ_{Grate}	-	1.05	1.06	1.10	0.80	1.07
$\dot{V}_{Air,Primary}$	10³ m³/h	40.2	40.2	40.3	30.0	40,2
$\vartheta_{Air,Primary}$	°C	180	180	180		130
$\dot{Q}_{Air,Primary}$	MW	2.5	2.5	2.5	1.9	1,8
$\vartheta_{G,Balance}$	°C	1,010	1,070	1,240	1,220	1,220
$q_{Loss,G}$	%	16.8	15.8	13.3	13.6	13,6
η_{Boiler}	%	72.1	73.5	76.3	76.2	76.2

Table 2. Calculated affect of process optimization. explanation in the text.

[4] This result confirms to theoretical calculations [7].

waste into the combustion control system[5] is shown in Table 2. States "1" and "2" are the original operational states (14:00 and 14:12 hours in Figure 5). States "2a", "2b" and "2c" represent optimized variations of state "2" - in these states the overall air ratio was reduced from λ_{Total} = 1.85 to λ_{Total} = 1.50. Differences between the optimized states are the stoichiometric air ratio of the grate λ_{Grate} and the temperature of preheated primary air to the grate $\vartheta_{Air,Primary}$.

The calculation results indicate that process optimization is possible by decreasing the total stoichiometric air ratio which will result in higher efficiency ratios for the boiler. In order to increase waste throughput the stoichiometric air ratio of the grate (state "2b") must be decreased and/or the temperature of the preheated air (state "2c") must be decreased. Since the stoichiometric air ratio of the grate is already low ($\lambda_{Grate} = 1.06$ in the operational state "2") lowering the temperature seems to be more appropriate in order to increase waste throughput. Boundary conditions and advantages of gasification in the primary combustion unit ($\lambda_{Grate} < 1$) and post-combustion in the secondary combustion unit of MSWI plants are described in detail in [2]. The additional steam saved in this process can be used to produce more electric energy within the turbines (with a corresponding reduction of bleeder steam). Additional boundary conditions that must be considered in this type incineration system (combustion / post-combustion) include: percentage of combustible materials in the ash residues (slag), the shift in heat transfer into the radiation part of the boiler (increase of $\vartheta_{G,Balance}$ in Table 2) and related effects on emissions (CO and NO_X formation, see also [2] and [8]).

5 Investigation of Process Optimization Measures

In order to increase the overall net energy output from an MSWI plant it is necessary to either reduce the demand of external energy to the system or to increase the production of heat and/or electric power (Figure 6). One easy way to increase the overall net energy output from an MSWI plant is to produce more electric power which can be accomplished by increasing the enthalpy difference between live and exhaust steam on the steam turbine. Since the live steam properties are dictated by the boiler design and operating temperatures the increase in enthalpy difference must be obtained by lowering the exhaust steam parameters (number 9 in Figure 6).

In the Schwandorf MSWI plant this optimization measure was implemented by increasing the capacity of the fans on the air cooled condensers in order to "sub-cool" the condensate. The subcooling of the condensate is limited by the design capacities of the fans as well as by the water content of exhaust steam (turbine blade corrosion increases with increasing water content).

[5] In existing combustion control systems the calorific value of waste is more estimated than calculated, based on measured values (oxygen content in flue gas, produced steam flow, temperatures at inner firing walls etc.).

It is difficult to estimate the effect on the energy efficiency of the plant with the implementation of this optimization measure because of the complex interferences between all the operating parameters. These parameters include higher energy supply to the air cooled condenser fans, the increase in electric energy production in the turbine, the increase in heat needed for condensate preheating and the improvement of thermal efficiency of the water steam cycle.

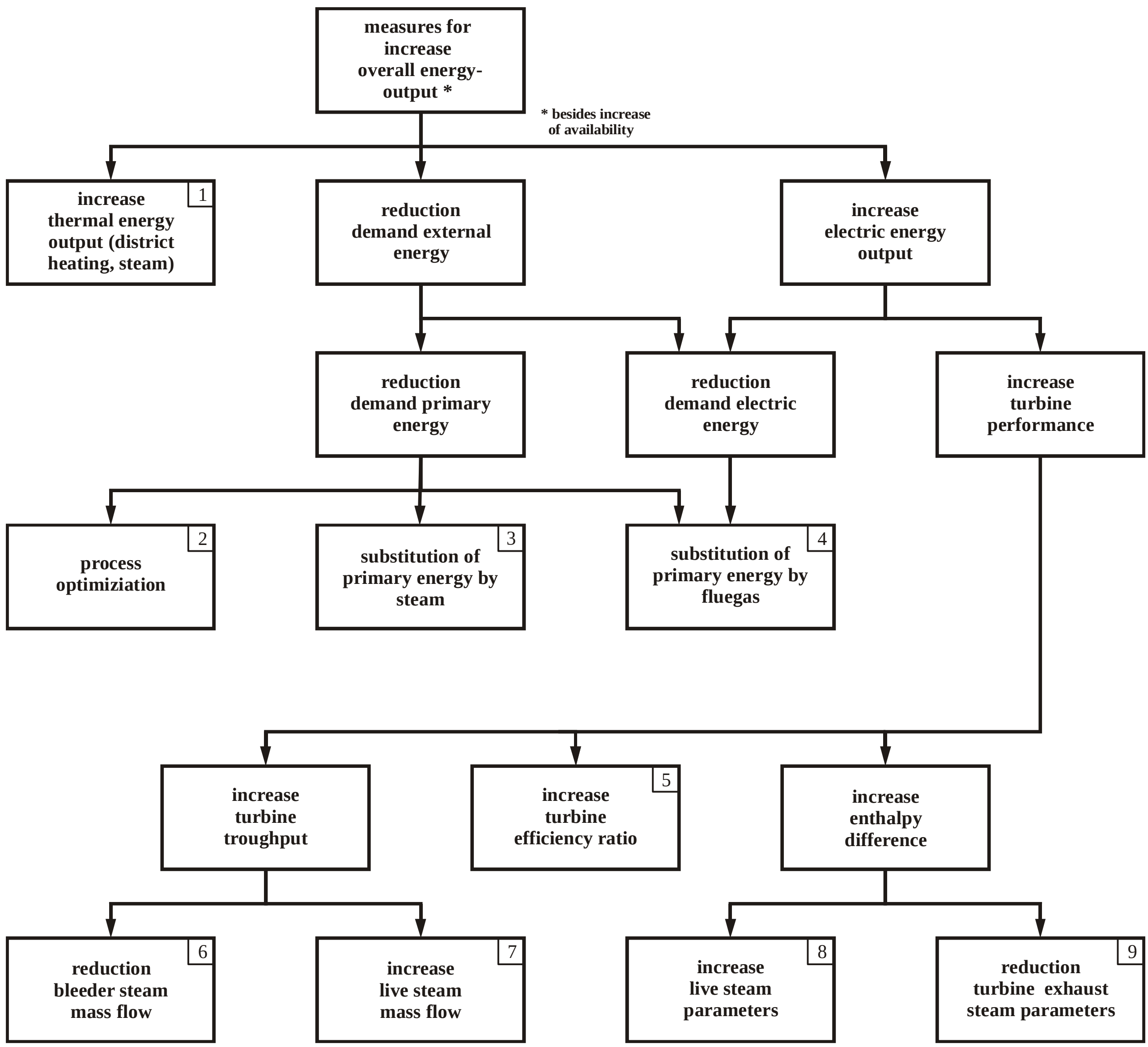

Figure 6. Methodology for measures to increase the net energy output of MSWI plants [8].

The calculated plant efficiency ratio (electric) and the water content of exhaust steam[6] plotted against the measured values of turbine exhaust steam temperature, electric energy to the fans on the air cooled condenser and the net electricity produced by the turbine is shown in Figure 7 for an investigation period of ½ hour. An approximately 800 kW increase of energy to the condenser fans results in this example in an increase in electric energy production of approximately 4 MW and

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[6] assuming evaporation equilibrium

therewith in a significant increase in energy efficiency of the plant from approximately 13.5 % to 16 %. The maximum water content of exhaust steam in this example was 12 %.

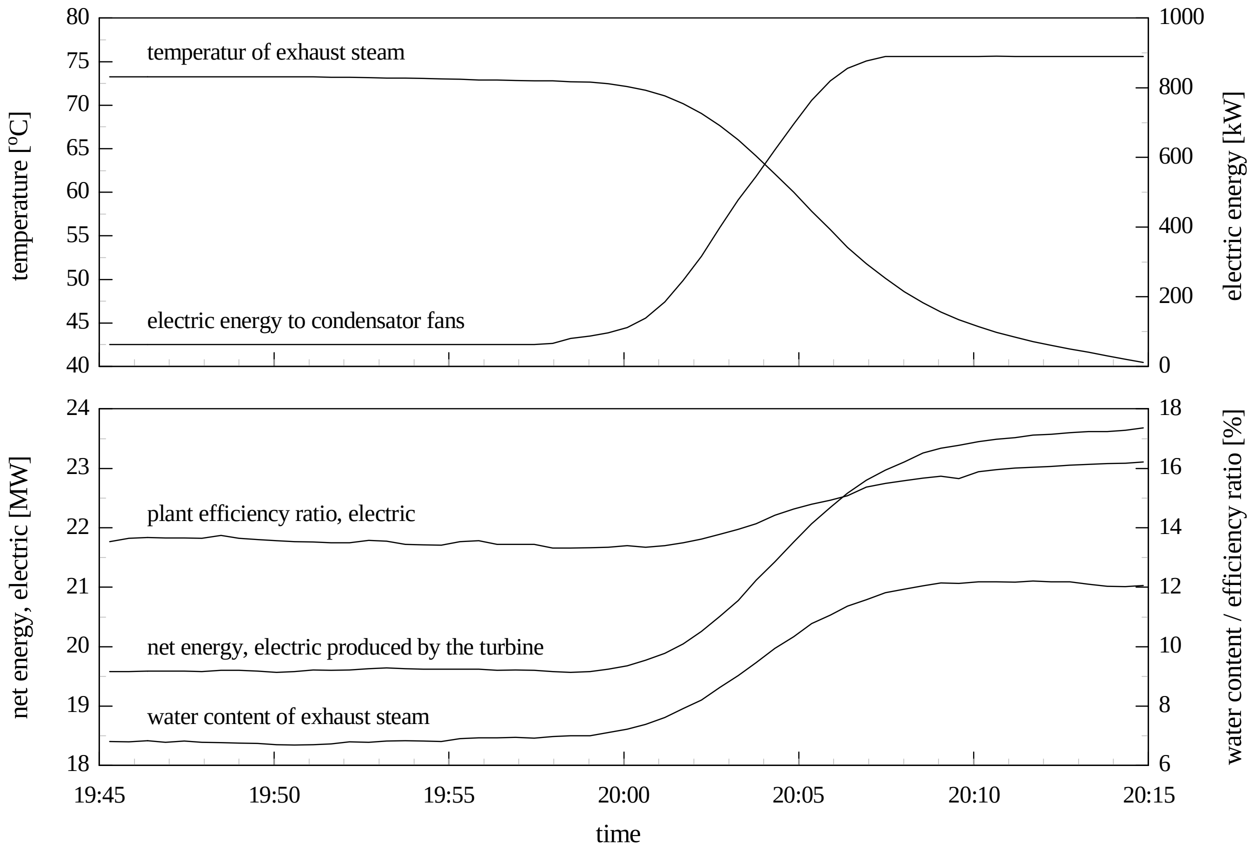

Figure 7. Reducing exhaust steam parameters in the MSWI plant Schwandorf - results of investigation.

It is obvious from this example that the Online-Balancing program has application in the optimization of the condenser performance in order to increase energy efficiency and to minimize the potential for turbine blade corrosion from water droplets. Additionally the program would assist in preventing the condenser from freezing in colder seasons. Therewith the program can be used to optimize the turbine-condenser performance under actual varying process conditions.

6 Conclusion

Additional testing and validation of the Online-Balancing program presented here is underway at the German MSWI plants in Schwandorf, Burgkirchen and Coburg [1]. The next step in the program development will be to test it at other MSWI plants. The user interface, calculation modules, and calculation strategies developed for the Schwandorf, Burgkirchen and Coburg MSWI plants will be used for this step. Consequently, the configuration and adaptation of the program for this plant will be much quicker. Due to the application of an easy-to-learn user interface, the program can be further adapted by operational staff without significant effort and also provide more details in specific balance units (e.g. water steam cycle, wastewater treatment, etc.). This is an advantage especially for those operational staff already using their own validation (evaluation) algorithms.

The next step in the development of the Online-Balancing program is to add simplified calculation methods for heat transfer in the boiler, kinetic in flue gas treatment, etc. in order to get a modelling and simulation program. The program is then effective at evaluating the complex interrelating primary operating parameters for a variety of plant configurations with the focus being on optimizing the overall plant. All in all, the operational staff now has an enhanced tool which can be used to optimize plant operations on a real time basis using comprehensive knowledge of the operations regarding energy efficiency, waste throughput, corrosion and operating costs.

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