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# A flue gas cleaning system's sufficiency under an increased thermal load

A case study on a Waste-to-Energy plant shifting to 120 % of nominal power

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<p>This thesis focussed on studying whether or not the capacity of Vantaa Energy's Waste-to-Energy plant's flue gas cleaning system would be sufficient for a 120 % thermal load. The project focussed on the process equipment supplied by a French company called LAB S.A., excluding some flue gas cleaning equipment such as flue gas condensers. This study is of interest for the company because the amount of municipal mixed waste produced at the moment in Finland and the Metropolitan region is greater than the incineration capacity. It is not allowed to place municipal mixed waste in landfills and thus, it would be beneficial for both Vantaa Energy and its waste supplier HSY to be able to combust more waste.</p> <p>The thesis was conducted by studying the mechanical flue gas flow operation ranges for the different process parts stated by the supplier in their contract and other documentation and by comparing it to the realized flue gas flow rate data during steady operation periods between September 2015 and March 2016. Also estimations of flue gas flow under the desired 120 % load were made and compared to the operation ranges of the equipment. ID fan fault situations were listed and studied separately because they were not included in the steady operation data.</p> <p>The main results were that for most process parts, a significant percentage (4,4–46,8 %) of observations have already exceeded the operation ranges of the equipment, while the boilers have been operated at the present maximum continuous load (110 % of nominal load). Extreme maximum limits have seldom been exceeded, but the estimated percentage of observations exceeding them under the desired 120 % load would also be significant for some process parts (0,7–35,5 %). The process equipment exceeding their operation range the most have been cooling towers. The stacks have exceeded their operation ranges the least. Contributory equipment such as conveying systems and silos have enough capacity to be operated under 120 % load.</p> <p>It seems risky to increase the load of the plant since it is already operating above its operation range for a significant percentage of time. System collapse situations would most likely become more frequent, and the economic benefit of the load shift might be compromised.</p>	
Keywords	Flue gas cleaning, Waste-to-Energy, increasing thermal load

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<p>Tämän insinööriyön tarkoitus oli tutkia Vantaan Energian jätevoimalan savukaasunpuhdistusjärjestelmän kapasiteetin riittävyttä 120 %:n kattilateholle. Työssä keskityttiin ranskalaisen alihankkijan LAB S.A.:n toimittamiin laitteisiin, joten työn rajauksen ulkopuolelle jäi joidakin savukaasunpuhdistuslaitteita, mm. savukaasulauhduttimet. Aihe on Vantaan Energialle tarpeellinen, sillä koko Suomessa ja myös pääkaupunkiseudulla polttokelpoisen sekajätteen tuotanto on suurempaa kuin polttokapasiteetti. Orgaanisia materiaaleja sisältävää jätettä ei saa enää sijoittaa kaatopaikoille, joten olisi sekä Vantaan Energian että yhteistyökumppanin HSY:n kannalta kannattavaa nostaa polttokapasiteettia.</p> <p>Projekti toteutettiin tutkimalla toimitussopimuksissa ja muussa dokumentaatiossa ilmoitettuja savukaasun läpivirtauksen maksimirajoja ja vertaamalla niitä toteutuneisiin savukaasuvirtaamiin vakaiden toimintaolojen vallitessa aikavälillä syyskuu 2015 – maaliskuu 2016. Savukaasuvirtauksen muutoksesta tehon noustessa 120 %:iin tehtiin arvio ja myös arvioituja virtauksia verrattiin laitteiden toimintarajoihin. Savukaasupuhaltimen romahdustilanteita tutkittiin erikseen, sillä ne eivät sisällyneet vakaan ajon aikaiseen dataan.</p> <p>Tärkeimmät tulokset olivat, että merkittävä osa (4,4–46,8 %) savukaasuvirtaushavainnoista on ollut laitteiden toimintakapasiteettien yläpuolella jo normaalilla maksimiteholla (110 %) ajon aikana. Jäähdytystornien toiminta-alue on ylitetty useimmin ja piippujen harvimminkin. Laitteille ilmoitettuja äärimmäisiä maksimirajoja ei ole ylitetty usein, mutta 120 %:n kuormalla myös kyseiset rajat ylittyisivät virtausarvioiden mukaan joidenkin laitteiden kohdalla merkittävän usein (0,7–35,5 % havainnoista). Avustavien prosessiosien kuten kuljetus- ja varastointilaitteiden kapasiteetti näyttäisi olevan riittävä 120 %:n teholle.</p> <p>Tehon nosto 120 %:iin olisi riski, sillä savukaasunpuhdistuslaitteisto toimii jo nykyisellään toiminta-alueensa maksimirajoilla ja sen yläpuolella. Prosessissa on koettu tilanteita, joissa toiminta on jouduttu keskeyttämään savukaasupuhaltimien suojaamiseksi. Lisääntyneet toiminnan keskeytykset saattavat vaarantaa tehonnostolla saavutettavan taloudellisen hyödyn.</p>	
Avainsanat	Savukaasunpuhdistus, jätevoimala, tehonnosto

## Contents

1	Introduction	1
2	Background	1
3	Waste-to-Energy plant design	4
3.1	Flue gas treatment plant design	5
3.2	General design basis of flue gas cleaning	7
4	Methodology	8
4.1	Assumptions	8
4.2	Flue gas flow change estimation	9
4.3	Waste amount estimation	16
5	LAB equipment	17
5.1	Electrostatic precipitator	18
5.1.1	Conveying system and storage of fly ash	22
5.2	Cooling tower	23
5.2.1	Water injection	24
5.2.2	Flow rate change	28
5.3	LAB-LOOP	30
5.3.1	Activated carbon storage and injection	30
5.3.2	Quick lime slaking, hydrated lime storage and injection	32
5.3.3	Flow rate and reaction time	37
5.4	Bag filters with residues re-circulation	38
5.4.1	Increased flow rate	39
5.4.2	Declogging	39
5.4.3	Contaminated ash re-circulation	40
5.4.4	Contaminated ash transport and storage system	42
5.5	Induced draft fan	44
5.5.1	Flow rate change	44
5.5.2	Behaviour of suction pressure and vibrations	44
5.5.3	Collapse situations	47
5.6	Stack	48
5.7	Emissions	49
6	Discussion and conclusions	53

7	Limitations and need for further study	56
7.1	Unreliability	56
7.2	Further study	57
	References	58
	Appendices	
	Appendix 1. ID fan collapse situations	

## 1 Introduction

At present the production of municipal waste requiring thermal treatment is greater than incineration capacity reserved for it in Finland. For this reason Vantaa Energy Ltd. is investigating the possibility to increase their Waste-to-Energy plant's waste combustion rate.

The aim of this thesis project was to study how Vantaa Energy's Waste-to-Energy plant's flue gas cleaning equipment would react to operating the plant at 120 % of nominal power. All process parts related to flue gas cleaning will be evaluated separately on the basis of how they would cope the power shift to 120 %. If any process parts will be found inadequate for use at 120 % power, estimations about their maximum load will be made.

The scope of this thesis is flue gas cleaning equipment, but it does not include everything that could be considered flue gas composition and pollution control equipment. A natural way to define the scope of this thesis was to concentrate on a contractor called LAB, who delivered most of the flue gas cleaning process parts. Some pollution control processes were thus ruled out, such as ammonia injection inside the boiler, flue gas recirculation and flue gas condenser.

Process equipment will mostly be evaluated on the basis of their design capacities and the sufficiency of different input and output material handling. Increases in corrosion or wear and tear of materials will not be considered.

## 2 Background

The new Finnish Landfill decree [1, 28 §] set on the basis of EU's Landfill Directive [2] states that any waste containing more than 10 % organic matter should not be placed in landfills anymore. The implementation date of the decree was January 1<sup>st</sup> 2016.

The amount of organic materials in source-separated municipal mixed waste in Finland is typically significantly larger than 10 %. According to HSY's most recent study about contents of mixed waste in the metropolitan region [3], the waste types mostly consisting of organic materials might sum up to as high as roughly 90 %. Even though mixed waste

composition varies throughout the country, it is clear that the amount of organic materials inside mixed waste is too high for mixed waste to be placed in landfills. Therefore, the new Landfill decree created a demand for waste incineration for treating municipal mixed waste before the remaining ashes can be placed in landfills (or used for land construction purposes).

At the moment there are seven (7) waste-to-energy plants running on mixed waste in Finland and two (2) plants under construction or in planning stage [4]. Their waste incineration capacities can be seen in Table 1 below.

Table 1. Waste incineration capacity in Finland [4]

<b>Location</b>	<b>Status</b>	<b>Capacity</b>
Kotka	Operational	100 000 t
Mustasaari (Vaasa)	Operational	180 000 t
Oulu	Operational	120 000 t
Riihimäki 1	Operational	150 000 t
Riihimäki 2	Operational	120 000 t
Tampere	Operational	150 000 t
Vantaa	Operational	320 000 t
Leppävirta	Under construction	145 000 t
Salo	Planning stage	110 000 t
Sum		1 245 000 t

Table 1 represents full capacities of waste-to-energy plants. From Figure 1 below it can be seen, that not all of the capacity is being used by municipal waste.

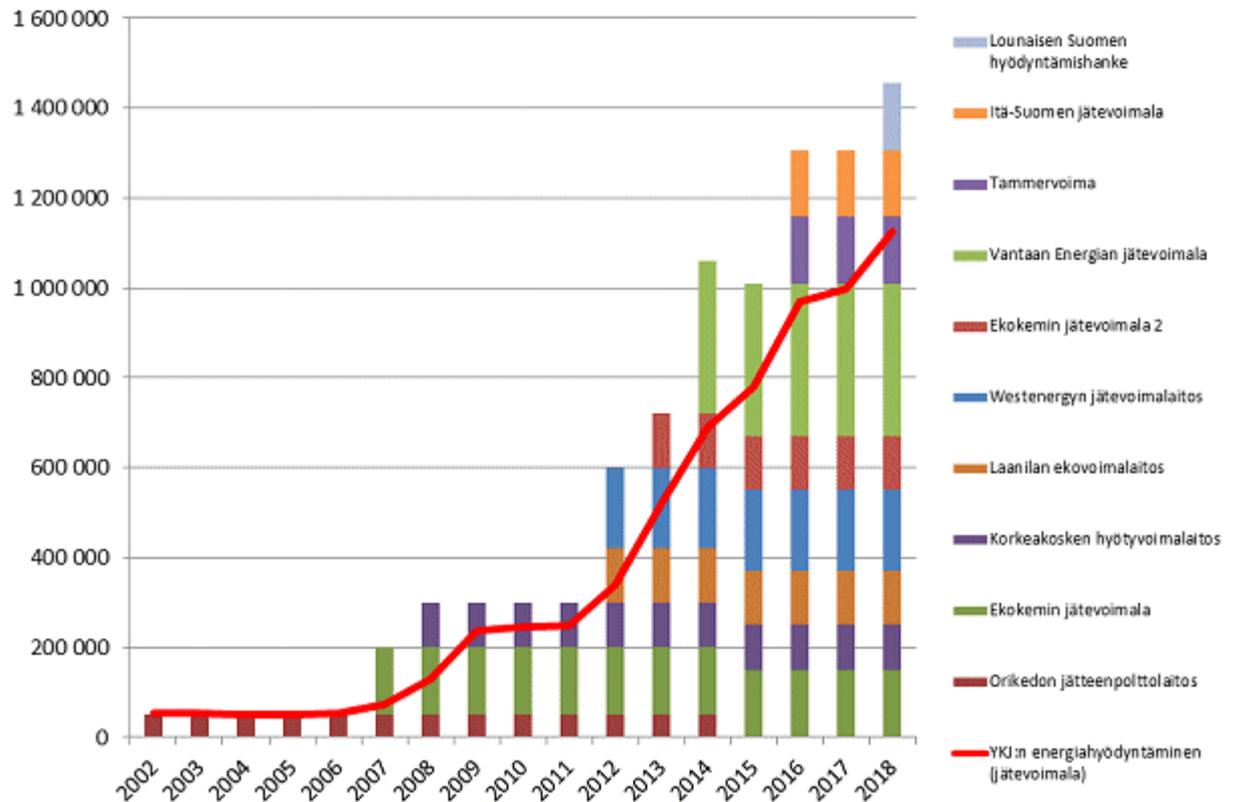


Figure 1. Waste combustion capacity in Finland by operational units and combustion capacity of municipal waste only [4]

Different colored bars in Figure 1 represent different waste-to-energy plants. Red line represents the capacity for municipal waste combustion, which is less than that for any waste, because legally 20 % of the waste a municipal waste company manages can come from parties that are not a part of the municipal waste handling system [5]. The remaining capacity in practice will be consumed by construction or industrial waste [4]. According to this figure the summed capacity for municipal waste combustion will be below 1 200 000 tons after the possible commission of Salo's waste combustion plant.

In addition to the waste-to-energy plants seen above, a gasification plant with a capacity of 250 000 tons per year is operational in Lahti [6]. Nevertheless, since it cannot use municipal waste as such but only after sorting and treatment as solid recovered fuel, it will not be included in these calculations.

A total of 2 616 000 tons of municipal waste was generated in Finland in 2014. Out of this amount, 856 000 tons were recycled and the remaining 1 760 000 was either land-filled or incinerated [7]. In Finland, waste materials are re-cycled based on source-separation, which means that consumers separate their waste to different bins. In practice,

since combustible material cannot be landfilled anymore and Finland lacks competing waste management technologies, the whole amount of un-recycled municipal waste should now be incinerated. By comparing the waste incineration capacity to waste incineration demand in Finland, it is clear that there is a need for additional incineration capacity. The situation applies also in Vantaa Energy's W-t-E plants collection area, because at the moment a fraction of municipal waste from South-Western parts of Finland is being transported to Vantaa [8]. By increasing the load of their W-t-E plant, Vantaa Energy seeks to meet this demand.

Vantaa Energy's W-t-E plant's original environmental permit was granted to combust 340 000 tons of waste per year. At the moment Vantaa Energy has a temporary permit to combust 374 000 tons a year. During the year 2015, a total of 343 668 tons of waste was incinerated [9].

### **3 Waste-to-Energy plant design**

Vantaa Energy's Waste-to-Energy plant was designed to meet a demand of incinerating 320 000 tonnes of mixed waste annually. It was officially taken into use in September 2014. The plant consists of two identical waste incineration lines with grate firing boilers of 58 MW each. In addition to the waste boilers, the plant also has a gas turbine (later abbreviated GT) – heat recovery steam generator (later abbreviated HRSG) –combination. The waste boilers can be operated independent of the GT-HRSG –combination. The gas turbine has 95 MW fuel power and 31 MW electricity power, and the heat recovery steam generator has 63 MW fuel power. When the GT-HRSG -combination is in operation, the fresh steam coming from the waste boilers can be heated up from ~400 °C to ~530 °C before directing it to the steam turbine, thus improving the performance of the steam turbine. The size of the steam turbine is 49,5 MW (electricity). The plant's efficiency is 95 % during full operation. The summed fuel power of the plant at full operation is 208,4 MW, consisting of 116,6 MW of waste and 91,8 MW of natural gas. Total electrical power is 80,5 MW (GT 31 MW and steam turbine 49,5 MW). Total district heating power is 119,3 MW (flue gas condenser included) [10]. Figure 2 depicts the layout of the plant.

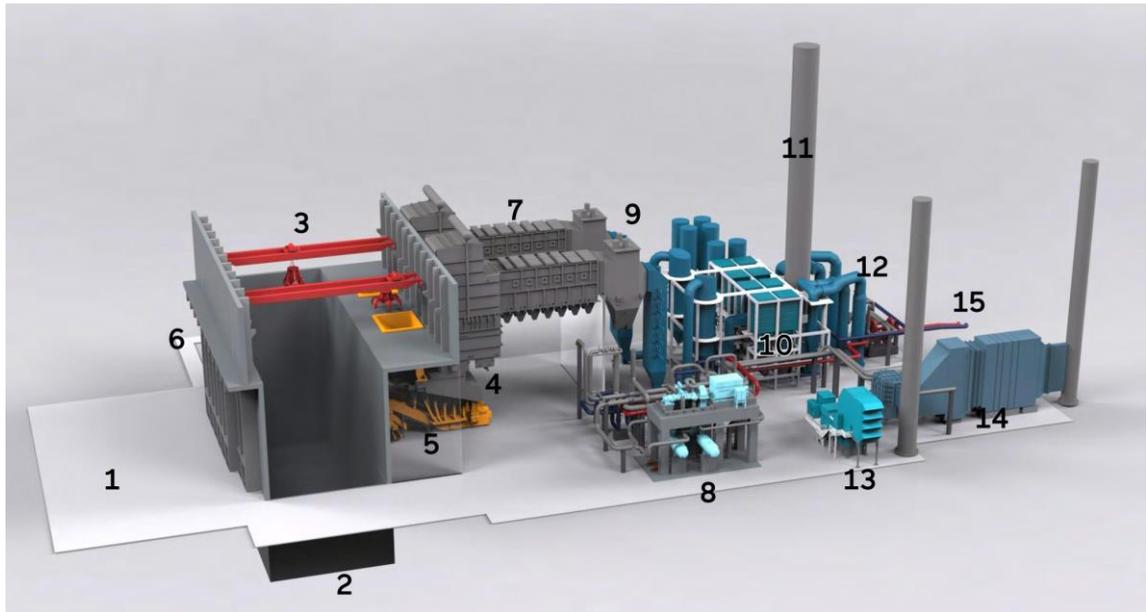


Figure 2. Waste-to-Energy plant layout

- 1 Waste reception hall
- 2 Waste bunker
- 3 Waste cranes and grabs
- 4 Grate and furnace
- 5 Slag (bottom ash) conveying system
- 6 Slag bunker
- 7 Super heaters, pre-heaters
- 8 Steam turbine and district heating heat exchangers
- 9 Electrostatic precipitator
- 10 Flue gas cleaning plant
- 11 Stack
- 12 Condenser
- 13 Gas turbine
- 14 Heat recovery steam generator
- 15 District heating inlet and outlet

### 3.1 Flue gas treatment plant design

Almost all process parts related to flue gas cleaning were purchased from a French company called LAB SA (later referred to as LAB). Corresponding to the boilers, flue gas cleaning system consists of two identical lines. Each line has an electrostatic precipitator

(later abbreviated as ESP), a cooling tower, dry reaction chamber called LAB-LOOP, four fabric filter chambers, a flue gas condenser and a stack. In Figure 2 most flue gas cleaning equipment can be recognized from dark turquoise colour but ESP has a grey colour (number 9 in Figure 2). In addition to these process parts, also for example ammonia injection inside boiler can be regarded as a part of flue gas cleaning system, because it is used to control  $\text{NO}_x$ -emissions. The scope of this thesis had to be defined so that it doesn't grow too vast, and it was decided that the most natural way to do this is to concentrate on the equipment purchased from LAB. This way the flue gas condenser is excluded, but all other flue gas cleaning parts outside the boiler are included in this thesis.

Figure 3 gives a more detailed view of the flue gas cleaning plant.

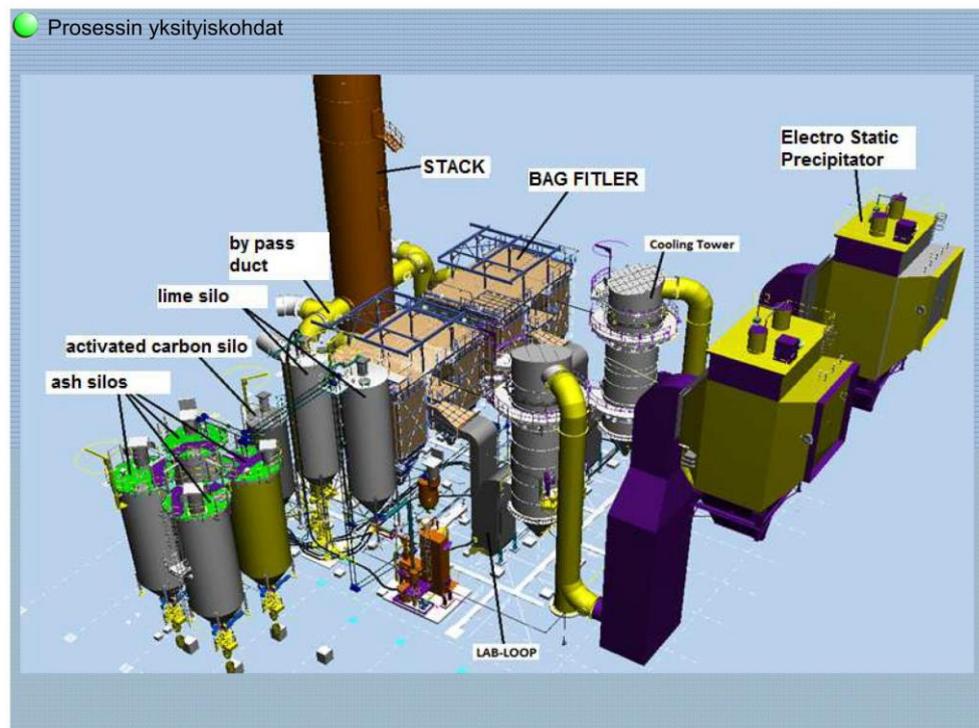


Figure 3. Flue gas cleaning equipment

As can be seen in Figure 3, there is a purple duct between the ESP and the cooling tower without any description. It is an economizer that is used to pre-heat water before entering the boiler. It is not LAB's equipment and thus will not be discussed in this thesis. One thing worthy of remark is, that to control  $\text{NO}_x$ -emissions, the plant also includes a flue gas re-circulation system, and the re-circulated flue gas is extracted after the ESP. This is why different flow conditions have to be applied for the ESP and the rest of the system.

### 3.2 General design basis of flue gas cleaning

The flue gas cleaning system is designed to operate under flue gas characteristic ranges (per line) shown in Table 2. Worthy of remark is that the notation 'STP' refers to 'standard temperature and pressure'. Also the notation 'Nm<sup>3</sup>' is used, and it refers to same conditions, even if in some sources letter 'N' might refer to 'normal' instead of 'standard'. In this context standard conditions refer to 0 °C and atmospheric pressure.

Table 2. Flue gas cleaning equipment operating ranges

<b>Electrostatic precipitator inlet</b>	<b>Operating range</b>
Flue gas flow	80 000 – 145 000 m <sup>3</sup> /h STP wet
Temperature	180-235 °C
Pressure	-2 - -15 mbar
<b>Flue gas cleaning plant</b>	
Flue gas flow	70 000 – 130 000 m <sup>3</sup> /h STP wet
Temperature	140-165 °C
Pressure difference, economiser	1 – 5 mbar

In addition to these values, an extreme maximum limit has been reported to be 159 500 Nm<sup>3</sup>/h for ESP inlet and 143 000 Nm<sup>3</sup>/h for cooling tower inlet [11]. Flue gas pollutant concentration ranges while exiting the boiler are presented in Table 3 below.

Table 3. Pollutant concentration operation range for flue gas cleaning equipment

<b>Pollutant</b>	<b>Daily average (mg/m<sup>3</sup> STP dry)</b>	<b>Half hour average (mg/m<sup>3</sup> STP dry)</b>
NO <sub>x</sub>	max. 250	max. 600
CO	max. 140	max. 50
NH <sub>3</sub>	max. 20	max. 20
TOC	max. 15	max. 15
HCl	800-2500	500-4000
HF	5-70	2-100
SO <sub>2</sub>	100-1000	50-1500
Dust	1000-4000	1000-6000

As will later be explained in detail, pollutant concentrations are assumed to stay at the same level after power shift.

## **4 Methodology**

The methods used in this thesis mostly consisted of studying different written sources to obtain needed information about the capacity of the flue gas cleaning system. The sources included supplier contracts, equipment/automation descriptions and books or articles about the field of waste-to-energy plant operation. Information (trends, control loops) from the plant's automation system, distributed control system (later referred to as simply DCS) was studied and used. Some calculations had to be performed and a mathematical software called MatLab was used to perform matrix operations on data extracted from DCS to simulate the flue gas cleaning equipment's behaviour under a greater load.

### **4.1 Assumptions**

The first assumption that had to be made was that the boilers would be able to fully combust the fuel needed to obtain a load of 120 %. Since the aim of this thesis was not to study the effect of the increased load on the boiler, nothing specific could be said about it. It is well possible that the load shift could cause problems in the boiler resulting in in-complete combustion. To be able to investigate whether flue gas cleaning equipment would be sufficient for a 120 % load, an assumption that the boiler could operate under this load had to be made.

The second fundamental assumption that was made for this thesis was that composition of waste would not change after the load shift. The same elemental analysis that was made for designing the plant will hold also at higher fuel consumption. In practice, this means that under a higher load, the combustion process would give the same ratios of compounds as the result as it does under the design loads. In practice, this means that the pollutant concentrations per unit flue gas flow would stay the same.

Even though investigating the boiler behaviour at a 120 % load is not in this thesis' scope, some things are worthy of remark. According to a designer and flue gas specialist working for boiler supplier Hitachi Zosen Inova (later referred to as Hitachi) [12], there are a few main factors to consider when estimating boiler behaviour and flue gas production rate under an increased load. First of all, the temperature of the flue gas exiting the boilers might increase due to insufficient thermal conduction and air injection capabilities of the boilers. The temperature of the combustion has an effect on the  $\text{NO}_x$  formation in direct correlation [13, 553]. This is why care must be taken to make sure that the temperature of the furnace does not increase too much. If air injection proves to be insufficient for the increased load, then relative decrease in air injection compared to fuel amount would also slightly decrease the total amount of produced flue gas. Another factor to consider is a recent effect that Hitachi designers have found in connection with excess air amount is that  $\text{NO}_x$  emissions can actually be reduced by decreasing the excess oxygen amount in the flue gas slightly from 5-7 %, which is at the moment considered as the optimum surplus (in Vantaa Energy W-t-E plant the set point for surplus oxygen is 5,8 %). Thus, if the air injection system's capacity would be insufficient for the increased load, it might have a diminishing effect on  $\text{NO}_x$  emissions. Increasing fuel consumption would most probably result in thickening of the waste bed on the grate which might impair the completeness of combustion, which would then result in relative diminution of flue gas production. The boilers and their design should be comprehensively studied to be able to assess which of these effects would be of significant nature. Because that is not in the scope of this thesis, a simplifying assumption has to be made that at 120 % continuous load the combustion would remain as complete as it is at lower loads and that the possible changes in  $\text{NO}_x$  content and temperature of the flue gas would be moderate and within operation limits of the system. If the combustion remains as complete as in lower loads, then flue gas flow would increase proportionally to the amount of the combusted fuel.

#### 4.2 Flue gas flow change estimation

Flue gas flow rate is a parameter for almost all flue gas cleaning plant equipment control loops. This means that different process parts are automatically controlled by different calculations performed by DCS, and a great part of these calculations contain flue gas flow as a parameter. It was important to make a plausible estimation of flue gas flow at 120 % load.

The design basis for the boilers has been that the fuel consumption behaves linearly with the thermal capacity load. This means that there is a direct correlation between fuel consumption and thermal capacity load with identical slope. The fuel consumption at 100 % thermal capacity is set to be 20 t/h per boiler [14, 3.1]. Operating continuously at 120 % would then mean a consumption of  $1,2 \cdot 20 \text{ t/h} = 24 \text{ t/h}$ . The flue gas flow would also increase in direct correlation because the fuel composition and excess oxygen in flue gas are assumed to stay at the same level. Thermal capacity at NCR is 58,3 MW [14, 4.3.1].

There are different load levels that have been defined by the boiler supplier Hitachi. The contract with Hitachi includes information about nominal continuous rate (later abbreviated NCR, 100 %) and maximum continuous rate (later abbreviated MCR, 110 %). NCR is what the boiler is optimized for, and MCR is the maximum load that the supplier guarantees the boiler can be operated at continuously. The contract also states that the boiler design allows for the boiler to be operated at 120 % (maximum momentary rate, later abbreviated MMR) for a maximum of two hours per day, but no design values are supplied.

Hitachi has estimated the flue gas flows before/after recirculation to be 117 627 / 101 137  $\text{Nm}^3/\text{h}$  at NCR and 129 521 / 111 155  $\text{Nm}^3/\text{h}$  at MCR [14, 4.8]. According to Hitachi's contract, the volume of flue gas requiring treatment is reduced by approximately 20 % by means of flue gas re-circulation. The actual amount depends on the calorific value of the waste and the thermal load at which the incinerator is operated [14, 4.2]. When determining the design values for flue gas production in NCR and MCR conditions, Hitachi has used a coefficient of 0,14 for the amount of flue gas re-circulation. Thus, it is assumed that the same coefficient can be used for higher load estimations as well.

The main operating parameters under different loads according to design values are presented in Table 4 as designed for NCR and MCR load and as estimated for MMR load (in brackets).

Table 4. Main operating parameters for different loads

<b>Parameter</b>	<b>100 % NCR (nominal continuous rate)</b>	<b>110 % MCR (max. continuous rate)</b>	<b>120 % MMR (max. momentary rate)</b>
Waste feed	20 t/h	22 t/h	(24 t/h)
Steam production	75,5 t/h	83 t/h	(90,5 t/h)
Flue gas production	117 627 Nm <sup>3</sup> /h	129 521 Nm <sup>3</sup> /h	(~142 000 Nm <sup>3</sup> /h)
Flue gas after re-circulation	101 137 Nm <sup>3</sup> /h	111 155 Nm <sup>3</sup> /h	(~122 000 Nm <sup>3</sup> /h)

Realized flue gas flow rate measurement data was studied and compared to the design values. This was challenging, because the DCS does not measure the amount of flue gas produced by the boiler. Instead, flue gas flow rate is calculated using flue gas velocity at stack and other measurements. While studying the calculations involved in determining flue gas flow, it was noticed that the result of the calculation includes streams added to the flow after the boiler, such as cooling water and reagent injection air. Thus, in order to determine real flow from the measurement data, simple calculations of extraction and addition with measurement data of flue gas re-circulation, cooling water and air injection and reagent injection air had to be made to be able to compare the data to design values. These calculations were conducted in Excel.

Next, the data to be studied had to be chosen. The DCS collects measurements and calculated signals many times in a second, so it was not reasonable to study all data from a longer period of time. Still, it was preferred to study data from different seasons because according to an interview with shift manager Jari Järvinen, the temperature and moisture content of the fuel vary and affect flue gas production during seasonal changes [15]. It was also preferred to include different times of the plant operational cycle, because fouling of boiler and other equipment might influence flue gas characteristics [13, 196]. It can also be seen from Hitachi's contract that they have reported a lower outlet temperatures for flue gas after 800 operating hours and a higher temperature for flue gas after 8000 operating hours [14]. It was decided that time periods of steady operation between September 2015 and March 2016 will be chosen for the determination of flue gas flow range. The times following yearly maintenance last year's July were left out because it always takes a while to obtain normal operation after overhauls [15]. It was

decided to study 30 minute interval average values for two reasons; first, this way the amount of data would stay reasonable. Second, for example lime injection control loop includes using a sliding average of 30 minutes, so this way also simulating new conditions would be easier. The data obtained this way was 4270 values from line 1 and 4318 values from line 2.

The times of steady operation were found by comparing the steam generation set point and the actual produced steam. The operators control the load of the boilers by setting a desired steam generation rate. Everything else is adjusted according to this set point. To find times of steady operation conditions steam generation set point and measured value were plotted as a trend from period 1.9.2015-31.3.2016. An example of the trends can be seen in Figure 4. This plot shows one month of operation. Steam set point was plotted with black and actual steam generation with red. Collapses in steam production might result from collapses of the system or planned maintenance breaks.

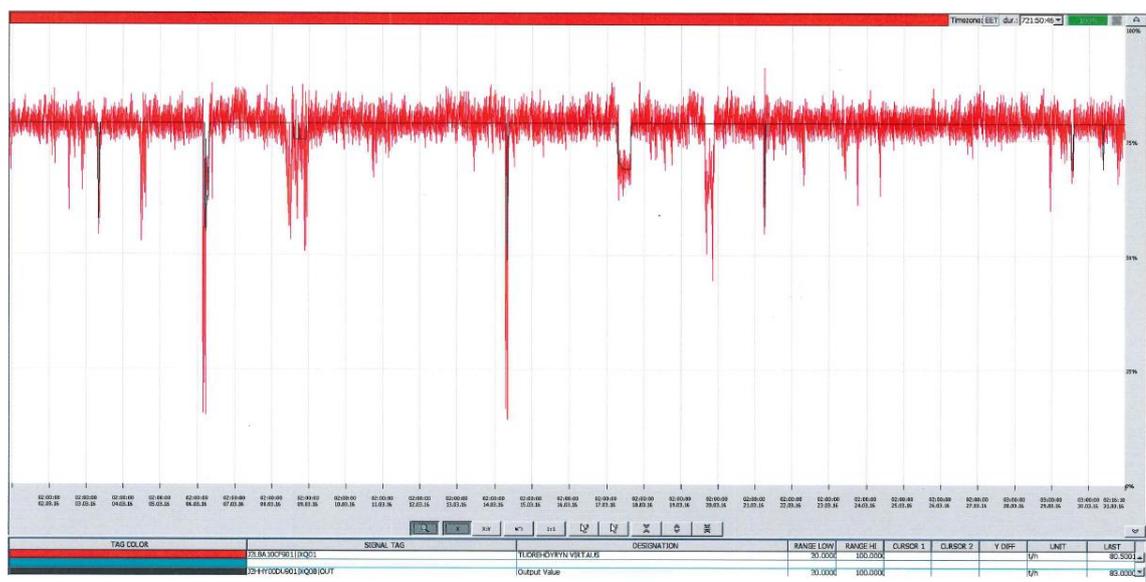


Figure 4. Example of steam set point and realized steam generation plotted against time

The load of the boilers can be seen from the set point for steam generation (~75,5 t/h at NCR and ~83 t/h at MCR) and during steady operating conditions the measured values vary in a small range around the set point. Comparing the set point and the measured values, it is easy to choose periods of steady operation.

Only full calendar days could be extracted from the automation system. During this period, only one interval of NCR load was found for each boiler, and it lasted for less than

a full day, and thus, it could not be included. The chosen steady operation intervals thus represent MCR and can be seen in Table 5.

Table 5. Chosen intervals of steady operation

Line 1	Line 2
6.9.-12.9.2015	4.9.-5.9.2015
1.10.-12.10.2015	15.9.-16.9.2015
25.10.-4.11.2015	6.10.-10.10.2015
6.11.-19.11.2015	19.10.-23.10.2015
27.11.-14.12.2015	12.11.-19.11.2015
29.12.2015-7.1.2016	22.11.-21.12.2015
7.2.-15.2.2016	24.12.2015-6.1.2016
25.2.-3.3.2016	8.2.-16.2.2016
22.3.-30.3.2016	20.2.-5.3.2016
	21.3.-30.3.2016

Also the following measurement/signal data was extracted from the same steady operation periods from both lines to be able to make calculations:

- moisture content of flue gas at stack, vol %
- moisture content at bag filter outlet, vol %
- temperature at stack, °C
- lime injection, kg/h
- cooling water injection, Nm<sup>3</sup>/h
- pressure difference over bag filters, mbar
- temperature at cooling tower inlet, °C
- temperature at cooling tower outlet, °C
- pressure before ID fan, mbar
- vibrations of ID fan, mm/s
- re-circulated flue gas flow, Nm<sup>3</sup>/h
- HCl and SO<sub>2</sub> concentration upstream wet, mg/Nm<sup>3</sup>
- HCl and SO<sub>2</sub> concentration downstream dry, mg/Nm<sup>3</sup>
- dust concentration at cooling tower inlet, mg/Nm<sup>3</sup>
- residues re-circulation, kg/h

It could be argued that to be able to assess the flue gas cleaning plants capacity to treat an increased flow, also the times of unsteady operation should be studied, because the process might have faced problems due to exceeding it's capacity. By experience, it is known though, that many of the process fault or collapse situations have occurred due to obstruction or vaulting problems in boilers rather than in flue gas cleaning plant [15]. Thus, it makes sense to leave most process collapses out of the scope because they do not represent normal operation and only seek for flue gas cleaning fault situations separately when needed. The flue gas cleaning plant collapse situations will be studied separately later in this thesis.

The flue gas flow at ID fan inlet at a 110 % load plotted as a function of number of measurements can be seen in Figure 5.

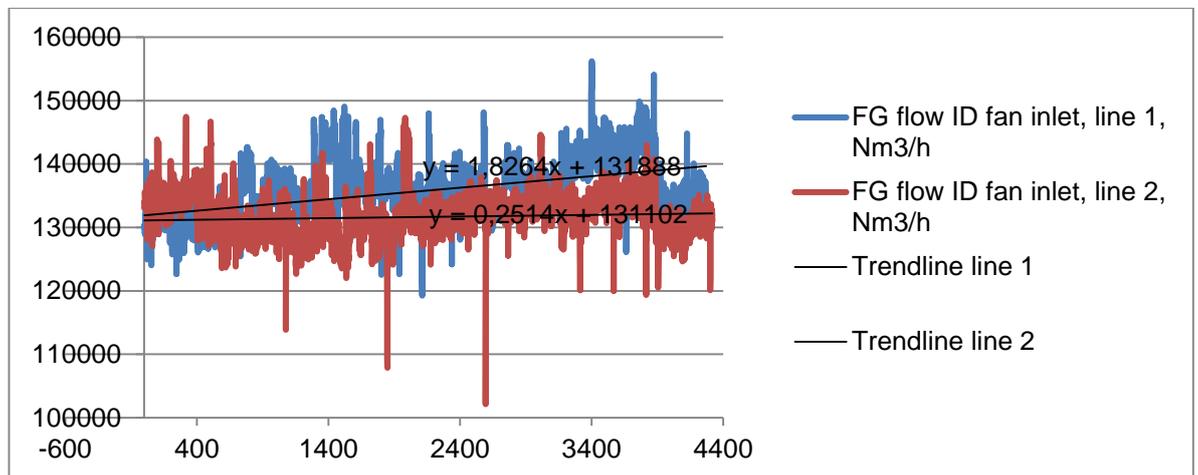


Figure 5. Flue gas flow plotted as function of observations

Since the x-axis is not continuous (all the shorter time intervals have been plotted one after another), the slope of the trends cannot be determined from this plot. However, it can be said, that during the steady operation periods of the plant the flue gas flow has been on the rise with time on both lines.  $R^2$  values of trend lines for lines 1 and 2 are 0,25 and 0,01 respectively, which means that both trend lines fit the data poorly, and thus the trends are not reliable. Since waste combustion is a complex process affected by many factors, it is logical that flue gas production's behaviour cannot be explained by single parameters.

A histogram was created to study the distribution of the flue gas flow data. From the histogram it can be seen that the distribution of the data resembles normal distribution.

The design operational range for flue gas flow at this point of process is 72 165-136 918 Nm<sup>3</sup>/h, and from the histogram it can be seen that a significant share of measurements during steady operation have exceeded this range. Figure 6 shows the histogram.

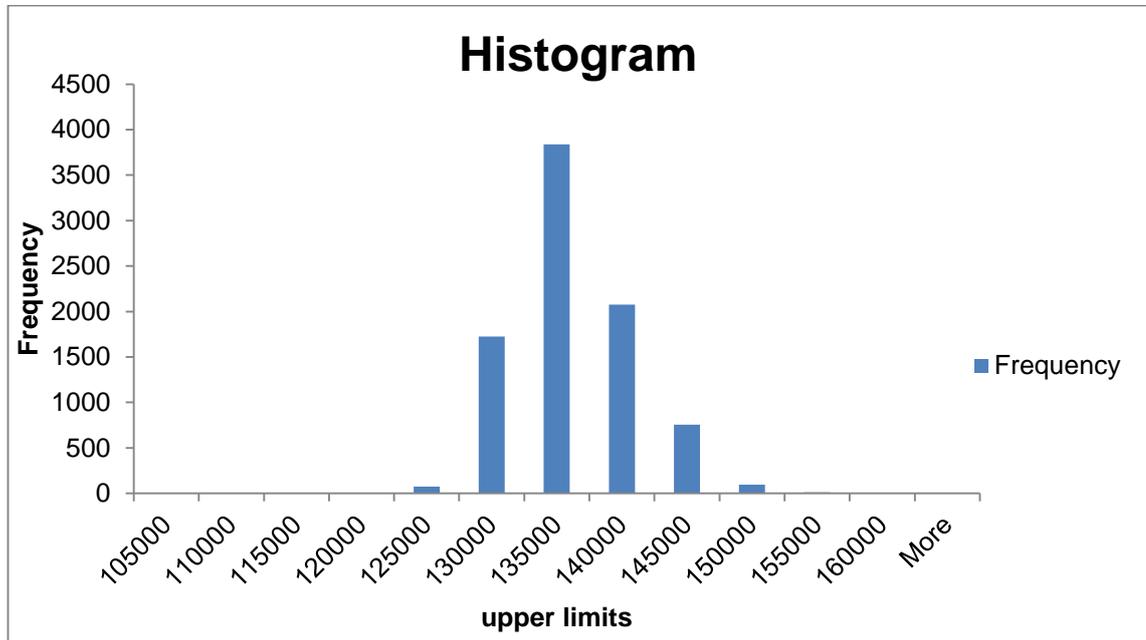


Figure 6. Frequency of flue gas flow observations

Since the flue gas flow measurement signal is located close to the end of the process, it includes air and water injections into the stream. To be able to study flue gas flow at different process points, injected streams had to be extracted from the signal. For example to obtain flow at ESP inlet reagent boosting air and cooling water + air –mix had to be extracted and re-circulated flue gas had to be added. Ranges of flue gas flow at a 110 % load and estimations of 120 % load at both ends of the process can be seen in Tables 6 and 7.

Table 6. Calculated flue gas flow ranges at ESP inlet

<b>110 % load ESP inlet</b>		<b>120 % load estimation ESP inlet</b>	
Minimum	99 700 Nm <sup>3</sup> /h	Minimum	108 700 Nm <sup>3</sup> /h
Maximum	169 500 Nm <sup>3</sup> /h	Maximum	184 900 Nm <sup>3</sup> /h
Average	143 100 Nm <sup>3</sup> /h	Average	156 100 Nm <sup>3</sup> /h

Table 7. Flue gas flow measurement and estimation ranges at ID fan inlet

110 % load before ID fan		120 % load estimation before ID fan	
Minimum	102 100 Nm <sup>3</sup> /h	Minimum	111 400 Nm <sup>3</sup> /h
Maximum	156 200 Nm <sup>3</sup> /h	Maximum	170 400 Nm <sup>3</sup> /h
Average	133 700 Nm <sup>3</sup> /h	Average	145 900 Nm <sup>3</sup> /h

Flue gas flow at other process points will be studied later in this thesis.

#### 4.3 Waste amount estimation

The process has been designed to incinerate 320 000 tons of municipal waste in a year. Environmental permit was granted for 340 000 t/a originally, but a 2-year temporary limit of 374 000 t/a was applied and granted during the year 2015. According to the contract between Vantaa Energy and boiler supplier Hitachi, the boilers are guaranteed to be available at least 96,1 % of the first two years of operation not taking into account the planned maintenance outages. This would mean at least the following:

$$t_g = 0,961 * (t_y - t_m)$$

where  $t_g$  is guaranteed available time in hours,  $t_y$  is possible operation hours in a year and  $t_m$  is hours of planned maintenance break. By substituting 8760 hours in a year and 336 hours (two weeks) of maintenance, a value of 8095,5 hours of operation per boiler is obtained.

In the year 2015 the boilers incinerated waste for 7977 and 7709 hours [9]. Let us assume that for the following years Vantaa Energy will reach at least the guaranteed annual availability. This would mean that the annual amount of combusted waste under continuous 120 % load would be:

$$2 \text{ lines} * 8095,5 \frac{\text{h}}{\text{a}} * 24 \frac{\text{t}}{\text{line h}} = 388 584 \frac{\text{t}}{\text{a}}$$

which is more than the temporary environmental permit allows. In the year 2015 the plant combusted 343 667,6 tons of waste [9]. By dividing with total operation hours of both lines this means an hourly average of 21,91 tons. This value is really close but slightly below the fuel consumption design value for 110 % load, which is 22 tons per hour. This

might be explained by operational problems and by heating value of waste. While designing the boilers it has been assumed that average lower heating value for the fuel is 10,5 MJ/kg ranging from 8 to 15 MJ/kg [14, 3.1]. During first full operational year 2015, lower heating value of waste was 10,8 MJ/kg on average [9]. Heating value is assumed to stay the same after load shift, but since the heating value has proved to be slightly larger than designed, it might have a small diminishing effect on the combusted waste amount.

## 5 LAB equipment

In this part, the different equipment will be studied systematically and separately estimating their behaviour at a 120 % continuous load. In Figure 7 we can see a diagram of the flue gas cleaning process.

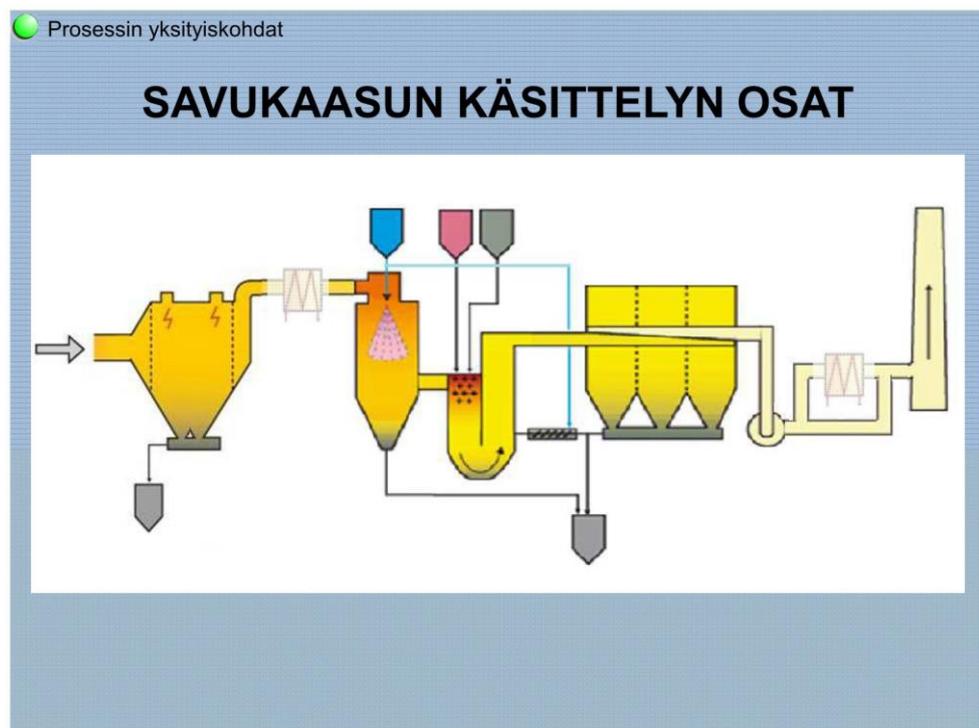


Figure 7. Flue gas cleaning equipment

Figure 7 also presents inputs and outputs of the process. Grey outputs below the process represent fly ash from ESP and cooling tower and residues or reaction products from bag filters. Blue input represents cooling water for cooling tower and humidifying residues

for re-circulation. Pink and grey inputs represent hydrated lime and activated carbon, which are injected into the reaction chamber to bind acidic compounds and heavy metals. An external economizer is situated between ESP and cooling tower, and a soot blowing mechanism used in it produces 6500 Nm<sup>3</sup> of steam per hour. This input is not included in the picture since economizer was not supplied by LAB but it has to be taken to account in calculations.

The maximum flow limits found in LAB documentation were compiled to a table for clarity (Table 8). The performance of the equipment cannot be guaranteed at extreme conditions, but mechanically the equipment should last.

Table 8. Separate operation ranges and extreme maximum limits for equipment

<b>Process point</b>	<b>Operation range (Nm<sup>3</sup>/h)</b>	<b>Extreme max. flow (Nm<sup>3</sup>/h)</b>	<b>Extreme max.temp. (°C)</b>
ESP inlet	80 000-145 000	159 500	235
Cooling tower inlet	70 000-130 000	143 000	165 (235 <sup>**</sup> )
LAB-LOOP inlet	70 250-131 889	145 055	160 (165)
Bag filters inlet	71 450-135 563	148 728	160 (165)
ID fan inlet	72 165-136 918	156 000*	160 (165)
Stack inlet	72 165-136 918	156 000*	175 (180)

\*different values found from different sources

\*\*depends on pressure

The values without brackets in temperature column represent extreme maximum continuous temperature and the values in brackets represent maximum exceptional temperature.

## 5.1 Electrostatic precipitator

The function of an electrostatic precipitator (ESP) is to move particulate matter to a collecting surface by the means of electric forces. Collection efficiency for particles in the range of 0,05-200 µm can be as high as 99%. However the efficiency of the process is better for large particles, since they can carry more charge than small particles [16, 91; 13, 595].

The function of the ESP in this particular plant is to decrease the amount of contaminated residues to be collected later in bag filters. The ESP has one (1) field and an active collection surface of 1350 m<sup>2</sup>. ESP uses the Corona effect to ionize gas particles with a negatively charged discharge electrode and collects them to a positively charged collecting electrode. The gas flows horizontally through parallel passages, and while crossing the passage, the ionized particles collide with dust particles and transport them to the collecting electrode. The ESP has two mechanical rappers operating on the outer walls, one on both sides of the device moving on a horizontal track. Collection surfaces are also cleaned with rappers. The dust falls down into hoppers and will be transported onwards by a conveyor screw to pneumatic transporting devices delivered by boiler supplier [17, 4.2-4.3; 18].

The separation efficiency of the ESP is designed to be at least 90 % or resulting in a dust concentration of less than 200 mg/Nm<sup>3</sup> or 170 mg/m<sup>3</sup> (dry 11 % O<sub>2</sub>) at the outlet. A measurement device to monitor the amount of dust exiting ESP is situated at the cooling tower inlet [17, 4.3; 18].

As described earlier, Waste-to-Energy plant's DCS contains parameters for flue gas flow after re-circulation at ID fan inlet and re-circulated flue gas flow, but not for flue gas flow before re-circulation. The signal for flue gas flow after re-circulation is calculated in a manner that results the flow rate to also include cooling water and lime and carbon injection air. These increase the flow but are injected into the stream after the ESP and had to be taken into consideration to be able to estimate increased load's effect on the ESP. Cooling water injection had a unit of volume per time as water, and it had to be converted into volume of steam at STP (standard temperature and pressure, 0° C and atmospheric pressure) to be consistent with other measurements' units and to know the effect on the flue gas flow. Volume of steam at STP could be calculated using the ideal gas law:

$$PV = nRT \rightarrow \frac{n}{V} = \frac{P}{RT}$$

where P is pressure in atm, V is volume in liters, n is molar amount, R is general gas constant and T is temperature in Kelvin. By substituting the parameters with values a molar volume of 0,044 mol/L is obtained. By multiplying with molar mass of 18 g/mol a

density of 0,794 g/L = 0,794 kg/m<sup>3</sup> was obtained. The final volume of steam could be calculated by dividing the amount of injected water in kilograms with the density of steam. This was done in Excel for all measurements. Injection air flows into cooling tower and reaction chamber were already in the correct units.

Flue gas flow at inlet of ESP had to be calculated by adding the flow of re-circulated flue gas and subtracting the portions of cooling water + air, LAB-LOOP reagent injection air and soot blowing steam from economizer. The obtained flow rates can be seen in Table 9.

Table 9. Observed and estimated flows at ESP inlet

<b>110 % load ESP inlet</b>		<b>120 % load estimation ESP inlet</b>	
Minimum	99 700 Nm <sup>3</sup> /h	Minimum	108 700 Nm <sup>3</sup> /h
Maximum	169 500 Nm <sup>3</sup> /h	Maximum	184 900 Nm <sup>3</sup> /h
Average	143 100 Nm <sup>3</sup> /h	Average	156 100 Nm <sup>3</sup> /h

As has been stated earlier, the design operation range of the ESP is 80 000-145 000 Nm<sup>3</sup>/h. Thus, it seems that ESP is already operating at the high end of its design capacity at 110 % thermal load. In addition to the operation range, a maximum extreme flow range was reported as 159 500 Nm<sup>3</sup>/h [11]. The performance of the equipment cannot be guaranteed at extreme conditions, but mechanically the equipment will last. According to 120 % flow estimations, the average flow would be slightly below the extreme flow limit under the increased load. Extreme limit value for inlet temperature is 235 °C.

How would the change in flow rate affect the velocity of flue gas inside ESP? The cross-section of the ESP is 6,8 m \* 5,7 m = 38,76 m [18]. The duct cross-section in this part of the process is relatively large to slow down the flow and thus increase ESP efficiency. To be able to estimate flue gas's velocity, the flow rate had to be converted from standard conditions to volume at actual conditions of the system. In practice the temperature at ESP inlet is stated to be 202-235° C rising with fouling. An average of these values was chosen as an approximation. Thus the volume flow rate can be obtained from:

$$Q_{actual} = Q_{STP} * \frac{273 K + T}{273 K}$$

where  $Q_{\text{actual}}$  is the actual volume flow at given temperature,  $Q_{\text{STP}}$  is volume flow at standard pressure and temperature and  $T$  is the temperature at actual conditions. By substituting average flue gas flows at MCR and MMR (estimated) and average temperature of 218,5 °C actual flows of 257 600 and 281 000 Am<sup>3</sup>/h were obtained.

Velocity of flue gas can be calculated from:

$$Q = A * v \rightarrow v = \frac{Q}{A}$$

where  $Q$  is volume flow (Am<sup>3</sup>/h),  $A$  is cross section area (m<sup>2</sup>) and  $v$  is velocity (m/s). By substituting with earlier obtained actual flows at MCR and MMR and cross section area of 38,76 m<sup>2</sup> velocities of 1,85 m/s and 2,01 m/s were obtained.

The velocity change of flue gas inside the ESP would increase from 1,85 m/s to 2,01 m/s under estimated flue gas flow at a 120 % load compared to an average speed at a 110 % load. The maximum measured flow under steady operation conditions at 110 % load was 169 500 Nm<sup>3</sup>/h, which means the average flow at 120 % load has already been experienced by the system.

The book Combustion and Incineration Processes by Walter R. Niessen [13, 597] states that there is a formula that can be used to predict ESP's efficiency:

$$\eta = 1 - e^{-\frac{A_0}{Q} * w}$$

where  $A_0$  is the collection area (m<sup>2</sup>),  $Q$  is flue gas flow rate (m<sup>3</sup>/s) and  $w$  is the particles' migration velocity. This formula is stated to work best for efficiencies below 95 %. From this formula it can be seen, that if the only thing to change is increasing flue gas flow then in theory efficiency should increase.

Pöyry has conducted performance tests on the ESP's at two occasions during years 2015 and 2016 [19]. Their results indicate that the ESP's particulate separation efficiency is not on the level that is stated in the contracts. The contract guarantees a separation efficiency of >90 %, but the tests show that in reality it is in the range of 61-67%. This level of performance deficiency probably has a significant effect on the fouling of the equipment in the following process equipment. Fly ash in flue gas might accumulate in

places where it will interfere with flue gas flow [13, 196]. In practice this means that the required pressure difference created by flue gas fans will increase.

There are many possible reasons for low performance of the ESP. According to literature, it is common to have multiple fields in municipal incinerators and in general newer units usually have 2-5 fields. The overall efficiency of ESP increases with the number of fields [13, 596]. As Vantaa Energy's W-t-E plant's ESP's only have one field, it seems like an exceptionally low amount for an application of this size.

#### 5.1.1 Conveying system and storage of fly ash

The LAB contract states that the design capacity of the conveying system shall be at least 140 % of the maximum fly ash production rate [17, 3.2]. The capacity of the screw conveyor under ESP was checked, and it is 3,5 t/h or 5 m<sup>3</sup>/h [20]. The density of fly ash is assumed to be 700 kg/m<sup>3</sup> and the reference production under MCR (110 %) load 406 kg/h (ESP+boiler) or an extreme maximum of 644 kg/h [21]. Conveying system seems over-dimensioned indeed and it shouldn't be a problem to increase the load.

There is one fly ash silo for each line. The size of the silos couldn't be found from contracts or other process description materials nor could it be found on site. Silo level behaviours were studied using DCS. Their ash levels were plotted against time for the month of March 2016 to see how often they have been emptied. Blue and green line in Figure 8 show the fly ash silo levels (the other lines depict contaminated ash silo levels).

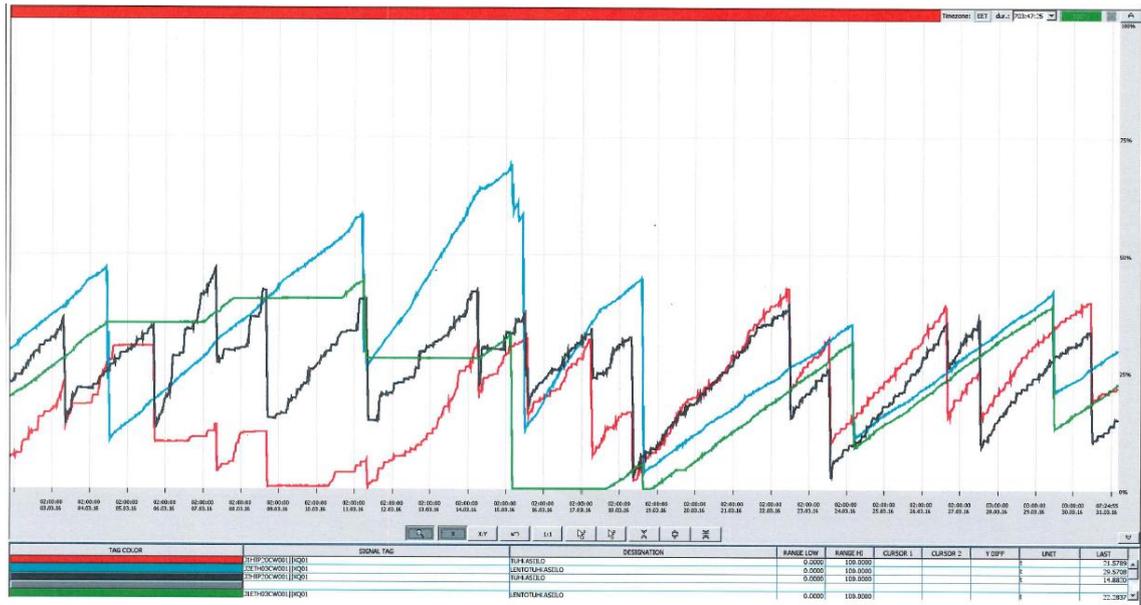


Figure 8. Ash silo levels during March 2016

Fly ash silos for lines 1 and 2 were emptied five and six times during March 2016. For the most time silo levels were kept under 50 tons, but the highest level for line 2 silo was roughly 70 tons. The silos getting full too often with increased ash productions would not create a problem for the process, because the silos can be emptied much more frequently if a vessel vehicle is ordered on site more frequently. The automation of the pneumatic ash transporting system should be studied in detail though to know how frequently the ash badges can be transported to the silo. That should not create a problem either though since the conveying capacity is stated to be at least 140 % of maximum production.

Even if the increased production of fly ash would not result in technical problems, it should be kept in mind that it would cause additional costs due to fly ash handling fees.

## 5.2 Cooling tower

Flue gas is humidified and cooled down to a temperature of about 140° Celsius in a cooling tower. Water at ambient temperature is injected into the flue gas stream and heat is absorbed into the evaporating water. Humidifying and cooling flue gas makes the conditions for the following chemical reactions with reagents (lime and activated carbon) optimal. The amount of injected water has a range of 0-1,5 Nm<sup>3</sup>/h and is controlled by temperature measurement at outlet of the following reactor. Residence time for flue gas

in cooling tower is designed to be 4-7 seconds. Water is injected into cooling tower via dual flow nozzles for both water and pressurized air. The system contains three (3) water injection pumps; one for both lines and a shared spare pump [17, 4.2; 18].

### 5.2.1 Water injection

Water injection in cubic meters STP during the steady operation conditions can be seen in Figure 9.

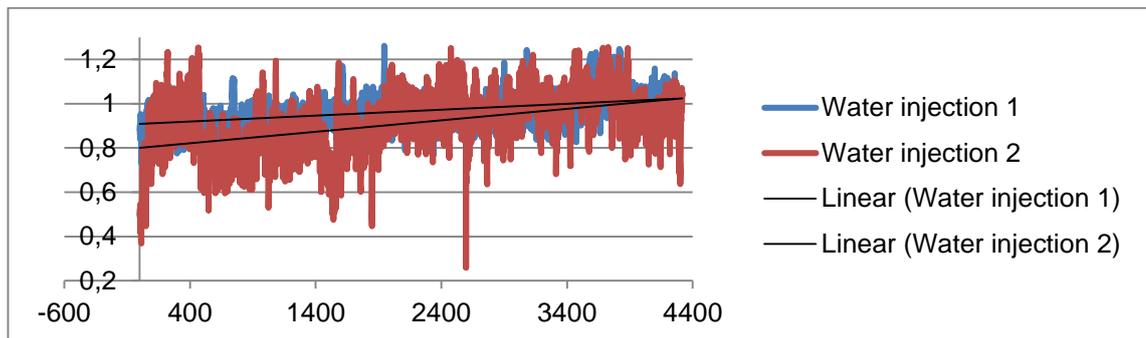


Figure 9. Cooling tower water injection as a function of observations

The amount of data values is so large that it is impossible to see anything from the data by eye. From the added trend lines it can be seen that water injection has been increasing with time. The rate of change cannot be determined from this plot, because all the values from different time intervals were simply plotted after each other. In other words the time (or number of measurement) on x-axis is not continuous. The real slope of the trend would be much narrower and could also change its sign because there would be more measurements in between the chosen time intervals.

The following estimations were made assuming that the temperature of the flue gas would remain on the same level after the load shift and that the fluctuation of flue gas flow and temperature would have similar trends than at MCR. With that assumption water injection would simply increase at the same ratio as flue gas flow. The obtained water injection ranges can be seen in Table 10.

Table 10. Water injection ranges

110 % water injection		120 % water injection estimation	
Minimum	0,260 Nm <sup>3</sup> /h	Minimum	0,283 Nm <sup>3</sup> /h
Maximum	1,261 Nm <sup>3</sup> /h	Maximum	1,376 Nm <sup>3</sup> /h
Average	0,939 Nm <sup>3</sup> /h	Average	1,024 Nm <sup>3</sup> /h

According to these estimations, the injection rate of 0-1,5 m<sup>3</sup>/h would be sufficient even during peak occurrences. However, according to both literature and an interview with a boiler designer for Hitachi, the temperature of exiting flue gas likely increases while load of boiler increases. This is due to for example originally possibly insufficient heat transfer properties of chosen materials and increased insulation caused by increased accumulation of ash [13, 196; 12]. Thus it was necessary to consider how the temperature increase would affect water injection as well.

Hitachi's designed outlet temperature of flue gas under 110 % load is 147-155 °C increasing with fouling during 800-8000 operating hours. The data studied in this thesis included measurements of a vast period of time ranging from ~700 to ~5000 operating hours, so it should be possible to see this effect from the data. During these chosen times of steady operation the temperature of outlet flue gas varied from 138 to 147 °C. The temperature of flue gas seems thus to be lower than expected. In addition to that the temperature of flue gas at cooling tower inlet has been decreasing over time, which is contrary to what was expected. The temperature data can be seen in Figure 10.

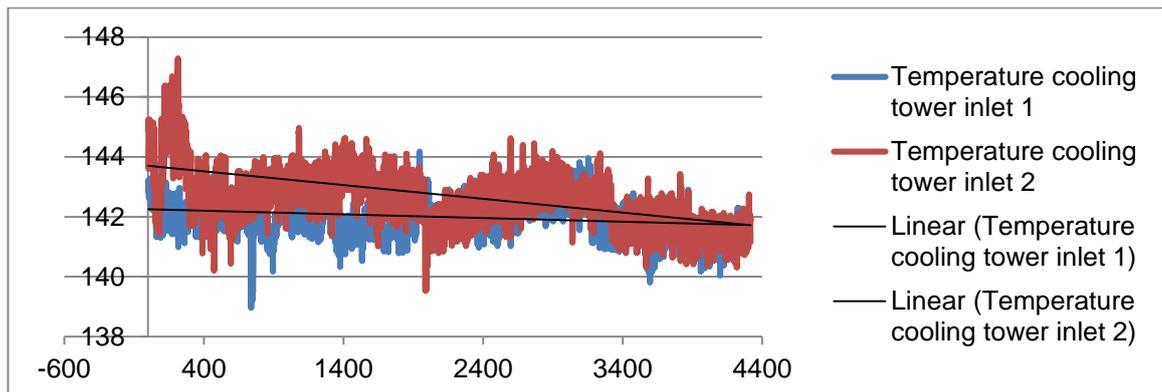


Figure 10. Temperature (°C) of flue gas at cooling tower inlet

This was surprising because the amount of injected water has increased over time. However, the increase in flue gas flow explains the increase in injected water. In an in-

interview with control room shift supervisor Kari Pulkkinen [22] it turned out that the temperature of flue gas exiting the boilers had been consciously reduced by controlling the super heater operation with more precision.

To be able to estimate sufficiency of cooling water an estimation about how much water it takes to cool down one unit of flue gas for 1 °C had to be made. It could be calculated using the data from DCS:

$$m_{w,s} = \frac{m_w}{\Delta T}$$

where  $m_{w,s}$  is specific water mass flow in kg/Nm<sup>3</sup> °C,  $m_w$  is realized water flow in kg/h,  $Q$  is volume flow of flue gas in Nm<sup>3</sup>/h and  $\Delta T$  is the change in temperature over cooling tower in °C.

An average of 0,002003 kg/m<sup>3</sup> °C of water was obtained with this calculation. The temperature of injected water is not monitored by the automation system. The calculation was tested by making an estimation of heat capacity of flue gas and calculating the temperature of injected water based on that to see if the temperature is reasonable. As the injection water is normal tap water, it's temperature is below 4 °C when it leaves the water treatment plant [23] but it gains some heat inside the distribution network and also at the plant's injection water tank before being injected. Heat capacity of flue gas had to be estimated by using heat capacities and design ratios of steam and air-like gases in flue gas (percentages by volume: 66,1 nitrogen, 17,7 steam, 10,4 CO<sub>2</sub>, 5,7 O<sub>2</sub> [21]):

$$C_{fluegas} = 0,177 * C_{steam} * \rho_{steam} + (1 - 0,177) * C_{air} * \rho_{air}$$

where  $C$  is heat capacity in kJ/kg °C and  $\rho$  is density in kg/m<sup>3</sup> in STP. Substituting with heat capacities of 1,901 and 1,0035 kJ/kg °C and densities of 0,794 and 1,275 kg/Nm<sup>3</sup> for steam and air respectively the result is 1,33 kJ/Nm<sup>3</sup>°C.

Also the heat capacity of injection water had to be estimated. Alongside with water, also air is injected into the stream, because pressurized air is used to produce fine droplets of water. The share of air with water had to be taken to account while determining the heat capacity of injection water. The average air injection in Nm<sup>3</sup> per each

kilogram of injected water was calculated for each observation using Excel. Average value was found to be 0,191 Nm<sup>3</sup>/kg. Thus the heat capacity of injection water+air mix per one kilogram of water becomes:

$$C_{comb} = C_{water} + V_{air} * \rho_{air} * C_{air}$$

where Cs are heat capacities in kJ/kg °C, V<sub>air</sub> is the average volume of air injected for each kilogram of water and ρ<sub>air</sub> is density of air. By substituting with already familiar values a heat capacity of 4,430 kJ/°C per one kilogram of injected water was obtained.

Since we know the needed mass of water to cool down one cubic meter of flue gas for one degree Celsius, the temperature difference of water+air mix could be calculated from:

$$E_{water} = E_{fg} \rightarrow \Delta T_{water} * C_{comb} * m_{water} = \Delta T_{fg} * C_{fg} * V_{fg}$$

$$\rightarrow \Delta T_{water} = \frac{\Delta T_{fg} * C_{fg} * V_{fg}}{C_{comb} * m_{water}}$$

where subscript 'fg' stand for flue gas, E is energy content in kJ, T is temperature in °C, C<sub>comb</sub> is the combined heat capacity of water and injection air in kJ/kg °C, m<sub>water</sub> is the mass of injected water in kg, C<sub>fg</sub> is heat capacity of flue gas in kJ/Nm<sup>3</sup> °C and V<sub>fg</sub> is the volume of fluegas in Nm<sup>3</sup>. Because we now know the amount of water it takes to cool one cubic meter STP of flue gas by one degree Celsius, we can substitute ΔT<sub>fg</sub> and V<sub>fg</sub> with value 1. With these values a temperature difference of 149,9 °C is obtained. Ofcourse this value cannot be true since the water will be ~140 °C when leaving the cooling tower and it cannot be in negative temperature when it enters the cooling tower. Thus it seems that something else must be absorbing heat from flue gas flow. Some fly ash will get attached to cooling tower walls while flue gas flows through, but the amount is so small that its heat capacity should be negligible. Since the calculation was checked multiple times and no errors were found, something must be absorbing heat in cooling tower.

The maximum cooling effect of cooling tower under higher flue gas flow was calculated as below:

$$Q * \Delta T_{max} * m_{injection} = m_{max} \rightarrow \Delta T_{max} = \frac{m_{max}}{Q * m_{injection}}$$

where Q is flue gas flow in Nm<sup>3</sup>/h,  $\Delta T_{max}$  is maximum temperature difference of flue gas,  $m_{injection}$  is the injected water in kg/Nm<sup>3</sup> °C and  $m_{max}$  is maximum water injection in kg. By substituting estimated average and peak flue gas flows at 120 % load, 0,002003 kg/Nm<sup>3</sup> for injected water and 1500 kg/h as the values, maximum temperatures of 5,13 °C and 4,40 °C for average and peak flows were obtained. Thus the capacity of the cooling tower would only allow the temperature of the flue gas to be 144-145 °C under 120 % load and remain sufficient cooling effect.

### 5.2.2 Flow rate change

According to LAB's flue gas data sheet, the continuous operating range of the cooling tower is 70 000-130 000 Nm<sup>3</sup>/h. Extreme maximum flow at inlet is stated to be 143 000 Nm<sup>3</sup>/h and extreme temperature maximum is 165 °C (depending on pressure even up to 235 °C) [11]. At LAB-LOOP inlet the extreme maximum flow is 145 055 Nm<sup>3</sup>/h, including cooling tower's water+air injection. The flue gas flow signal extracted from DCS contains water+air injection and also reagents feed air and de-clogging pulses of bag filters.

Flue gas flow rate at cooling tower inlet was calculated by extracting reagent boosting air and cooling tower water+air injection from the flue gas flow signal at ID fan inlet. The flow specs can be seen in Table 11.

Table 11. Flue gas flow at cooling tower inlet

110 % load flow at cooling tower inlet		120 % load estimated flow	
Minimum	99 200 Nm <sup>3</sup> /h	Minimum	108 200 Nm <sup>3</sup> /h
Maximum	152 400 Nm <sup>3</sup> /h	Maximum	166 300 Nm <sup>3</sup> /h
Average	129 900 Nm <sup>3</sup> /h	Average	141 800 Nm <sup>3</sup> /h

The estimated average flow at 120 % load is below the extreme limit set in LAB's documentation (143 000 Nm<sup>3</sup>/h at cooling tower inlet). However, in reality the flow after cooling tower has probably been slightly lower due to the effect of bag filter pulse air being included in the measurement.

The velocity of the gas inside cooling tower is relevant, because it is important that water has enough time to evaporate inside cooling tower. If the water leaving the cooling tower carries entrained water droplets, it may cause problems later in the system due to fly ash adherence and accumulation [13, 331]. The diameter of cooling tower is 450 cm and the cross section area is thus  $\pi \cdot (4,5 \text{ m}/2)^2 = 15,90 \text{ m}^2$ .

To calculate velocity of flue gas, it's flow rate had to be converted from standard temperature and pressure (STP) to actual temperature and pressure. As with ESP, it can be done using the ratio of actual temperature to 273 Kelvin (see formula below). During chosen steady operation intervals the temperature of flue gas at cooling tower inlet varied from 138 to 147 °C having an average of 142,35 °C.

$$Q_{actual} = Q_{STP} * \frac{273 \text{ K} + T}{273 \text{ K}}$$

where  $Q_{actual}$  is the actual volume flow at given temperature,  $Q_{STP}$  is volume flow at standard pressure and temperature and  $T$  is the temperature at actual conditions. By substituting average flue gas flows at MCR and MMR (see Table 11) and average temperature of 142,35 °C actual flows of 197 700 and 215 800 Am<sup>3</sup>/h were obtained.

As with ESP, velocity can be calculated from:

$$Q = A * v \rightarrow v = \frac{Q}{A}$$

where  $Q$  is volume flow (Am<sup>3</sup>/h),  $A$  is cross section area (m<sup>2</sup>) and  $v$  is velocity (m/s). By substituting with earlier obtained actual flows at MCR and MMR and cross section area of 15,90 m<sup>2</sup> velocities of 3,45 m/s and 3,77 m/s were obtained.

Evaporation height is 12 m. The size of the droplets is stated to be <150 μm [18]. The evaporation time of water droplets can be estimated from the following equation [13, 333]. The highest design temperature of flue gas and largest size on water droplet were used.

$$t = \frac{r_d}{0,123(T - T_d)}$$

where  $t$  is residence time in seconds,  $r_d$  is droplet radius in  $\mu\text{m}$ ,  $T$  is temperature of gas ( $^{\circ}\text{C}$ ) and  $T_d$  is temperature of droplet ( $^{\circ}\text{C}$ ). Average temperature of entering flue gas and an estimated temperature of  $10^{\circ}\text{C}$  for droplet temperature were substituted and an evaporation time of  $9,2\text{ s}$  was obtained. The cooling tower is designed for a residence time of  $4\text{-}7$  seconds. The residence time for estimated average flow at  $120\%$  load would be  $12\text{ m} / 3,77\text{ m/s} = 3,18\text{ s}$ . So it seems that the velocity of desired flue gas flow would be too high to allow for design values of residence time in cooling tower. The design residence time seems to be too low to allow for the droplets to evaporate to begin with. Without more accurate information about the temperature of water or about actual droplet size, it is hard to say whether these estimations are close to reality or not.

### 5.3 LAB-LOOP

The next step of the process is a dry reactor called 'LAB-LOOP'. In LAB-LOOP hydrated lime and activated carbon are pneumatically injected into the flue gas stream. To insure turbulence to obtain sufficient mixing of flue gas and reagents the reactor is a U-shaped vertical duct. The reagents react with acid gases, heavy metals and dioxins/furans forming a powder that can be filtered out from the stream later [18; 17, 4.2-4.3].

LAB LOOP's operation range at inlet is  $70\ 250\text{-}131\ 889\ \text{Nm}^3/\text{h}$  and extreme maximum flue gas flow is stated to be  $145\ 055\ \text{Nm}^3/\text{h}$  and temperature  $160^{\circ}\text{C}$  continuously and  $165^{\circ}\text{C}$  during exceptional conditions [11].

#### 5.3.1 Activated carbon storage and injection

According to the contract with LAB, the reagent storage silos shall correspond to one week's reagent/absorbent consumption at nominal load [17, 3.2]. However, the consumption of activated carbon is so low that probably the activated carbon silo's capacity is larger.

Activated carbon is stored in a silo with the volume of  $70\ \text{m}^3$ . The density of activated carbon is  $450\ \text{kg}/\text{m}^3$  which means that the silo can hold  $31\ 500\ \text{kg}$  of activated carbon. The silo has a discharge capacity of  $30\ \text{kg}/\text{h}$  [17, 4.3].

Injection of activated carbon is simply controlled by the flue gas flow rate and the formula is the following [24]:

$$m_{carbon} = \frac{5,5 \frac{kg}{h}}{117\,600 \frac{Nm^3}{h}}$$

This means an injection rate of  $4,68 * 10^{-5} \text{ kg/Nm}^3$ . Estimated flue gas flow rate at 120 % load has an average of  $145\,900 \text{ Nm}^3/\text{h}$  and a peak maximum of  $170\,400 \text{ Nm}^3/\text{h}$ . By multiplying the activated carbon injection rate with these flow rates the average and maximum injection rates become  $6,8 \text{ kg/h}$  and  $8,0 \text{ kg/h}$  respectively. This means that the discharge capacity of the silo ( $30 \text{ kg/h}$ ) will not be exceeded. With the estimated maximum injection rate of  $8 \text{ kg/h}$  it would take roughly 164 days to empty the whole silo.

Figure 11 is a screen shot from the DCS system. It shows the activated carbon weight against time. This plot shows a 6 month interval.

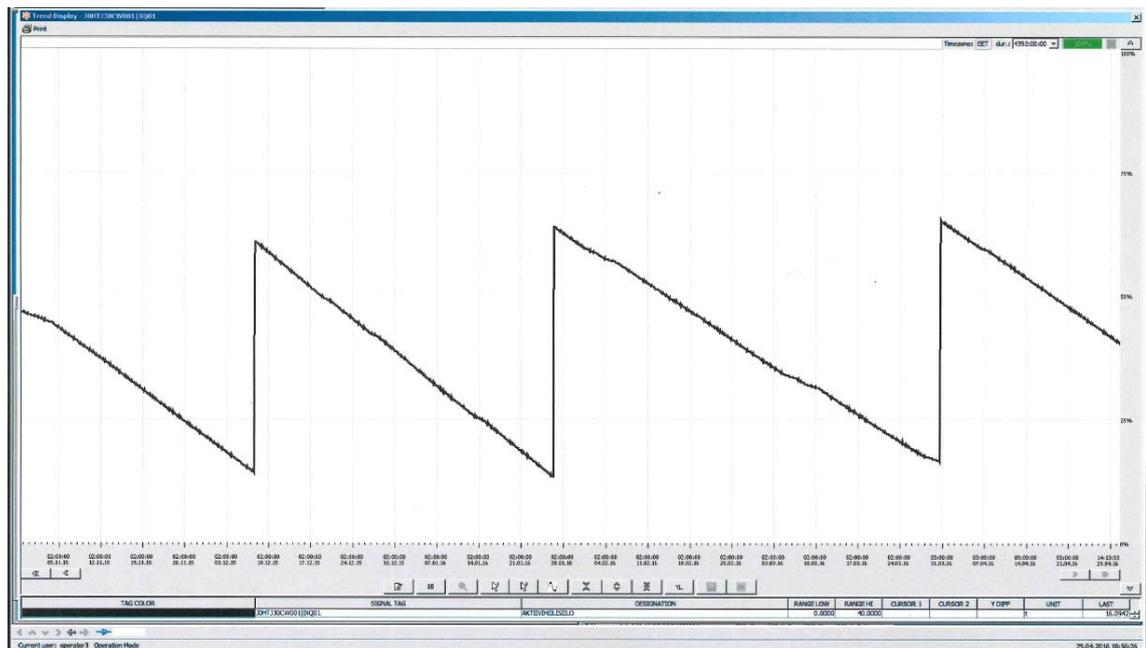


Figure 11. Activated carbon storage silo level against time

From Figure 11 it can be seen that the silo has been filled three (3) times during the last 6 months. This leads to the conclusion that increased activated carbon consumption under 120 % load would not make a significant change to the silo filling interval.

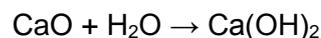
### 5.3.2 Quick lime slaking, hydrated lime storage and injection

According to LAB's contract, the quick lime storage silo has a capacity corresponding to 7 days' consumption at nominal load (7 days + 25 tons). The hydrated lime buffer silo has the same volume which should correspond to 3 days' consumption [17, 4.2].

The size of the quick lime silo is 130 m<sup>3</sup> and density of quick lime is assumed to be 900 kg/m<sup>3</sup>. Silo can thus hold 117 000 kilograms of quick lime. Silo's discharge capacity is 2500 kg/h. Quick lime is hydrated on site in a dry slaker that has the same slaking capacity: 2500 kg/h.

Hydrated lime silo is of the same size as quick lime silo; 130 m<sup>3</sup>. Density of hydrated lime is assumed to be 450 kg/m<sup>3</sup>. It's discharge capacity is 3500 kg/h. Silo capacity in mass is 58 500 kilograms.

Quick-lime and water are mixed in the slaker to produce hydrated lime. The chemical reaction is aggressive and relatively complete and takes place as follows:



Molar masses of quick lime and hydrated lime are 56,077 g/mol and 74,092 g/mol respectively. Each mole of CaO produces one mole of Ca(OH)<sub>2</sub>. The ratio of mass is:

$$\frac{74,092 \frac{g}{mol}}{56,077 \frac{g}{mol}} = 1,321$$

which means that each kilogram of CaO produces 1,321 kg of Ca(OH)<sub>2</sub> with water. To fill the hydrated lime silo it would thus take:

$$\frac{58\,500 \text{ kg}}{1,321} = 44\,285 \text{ kg}$$

of quick lime. With slaking capacity of 2500 kg/h it would take roughly 18 hours to fill the hydrated lime silo. Hydrating quick-lime is operated as a batch process, which means that for the most of time the slaker is in a stand-by mode but once the hydrated lime silo content reaches a low surface limit value, the slaker will be switched on to fill the silo. In

Figure 12 we can see the mass of CaO inside the silo during one month (April 2016). The silo has been filled five (5) times and the slaker has been on eight (8) times during April 2016. Increasing frequency of filling and slaking should not cause problems in the process.

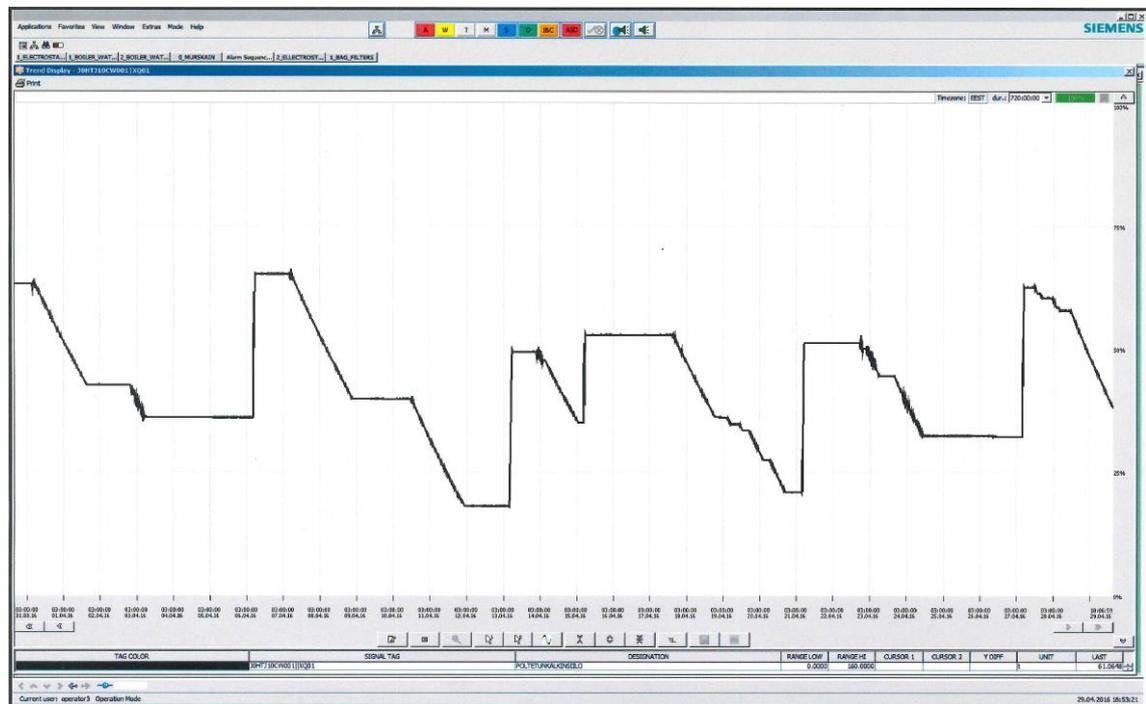


Figure 12. CaO silo level during April 2016

Data of hydrated lime injection rate was extracted from DCS. The data consists of two lime feeders per line; a base feeder and a peak feeder and in addition a common spare feeder. Each feeder has a capacity of 1100 kg/h. The spare feeder hadn't been used during the chosen time intervals. So to obtain the lime injection rates, the base feeder injection rate and peak feeder injection rate were summed. The lime injection plotted against the number of measurement can be seen in Figure 13.

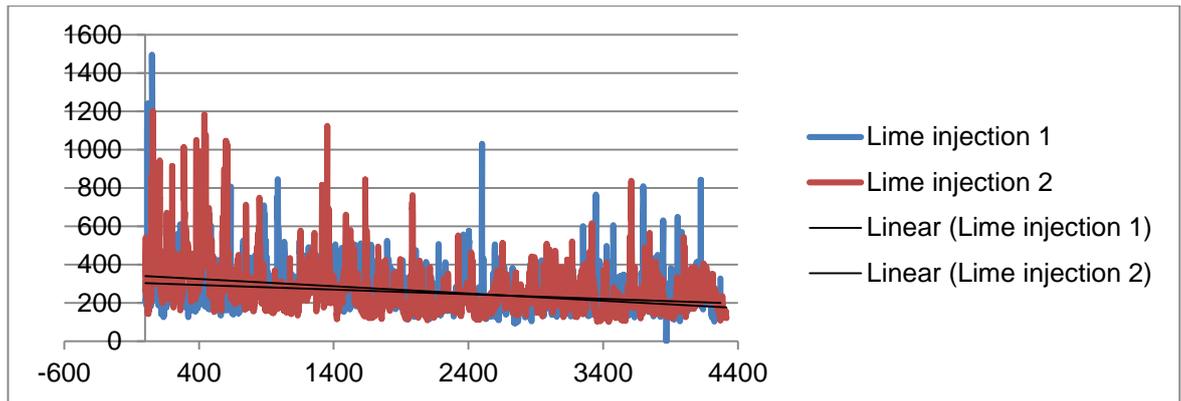


Figure 13. Hydrated lime injection rate as a function of observations

Both lines have a slightly diminishing trend as a function of non-continuous time.

Assuming that different combinations formed by all the other conditions except flue gas flow would stay the same, flue gas flow rate would be the only changing parameter and a rough estimation about hydrated lime injection change during steady operation could be done by multiplying the lime injection data with the same coefficient as flue gas flow to estimate behaviour under 120 % load. Injection rates can be seen in Table

Table 12. Hydrated lime injection rates

110 % lime injection		120 % load lime injection estimation	
Minimum	0,77 kg/h	Minimum	
Maximum	1497,05 kg/h	Maximum	1633,09 kg/h
Average	255 kg/h	Average	278,18 kg/h

The average consumption has been low compared to maximum feed capacity of 2200 kg/h. Maximum feed during steady operation is 68 % of the maximum feed capacity. It has to be kept in mind though that the data only contains steady operation time intervals, and since high lime injection rate might increase likelihood of problems with ID fans the excluded un-steady operation intervals might include times of higher lime injection.

Because the conditions affecting hydrated lime injection can vary and form different combinations by chance, it was of interest to find out whether the hydrated lime injection system would be sufficient in the worst possible scenario under 120 % load. The behaviour of lime injection control loop is much more complicated than that of activated carbon control loop. Thus it proved to be really difficult to simulate the lime injection behaviour

under the desired 120 % load. The amount of lime injected to the LAB-LOOP is calculated by a programming loop, that uses for example measured HCl and SO<sub>2</sub> upstream and downstream concentrations in flue gas flow as it's input and gives the lime injection rate set point as output. Data about real lime injection measurement could be extracted from DCS, but not lime injection set point. Lime injection set point was attempted to be simulated by using measured data from DCS as input vectors and then conducting the same calculations on the vectors as the control loop does on the measurements continuously while operation. By changing the flue gas flow to correspond to the estimations of 120 % load, it should be possible to simulate the behaviour of the lime injection system roughly. The calculations involved in the control loop had to be studied with the help of LAB's design documentation because the structure of the control loop couldn't be comprehensively seen from the user interface of the automation system. As a result of the MatLab script a vector of lime injection rates could be attained. It was found that the simulated set point values at 110 % operation conditions were roughly 30 % higher than the measured lime injection rates. The first thing to do was check whether the set point data was in accordance with the feeding screw data. Data about the set point of lime injection could not be extracted from DCS, but the signal could be plotted against the injection screw data in the user interface. An example of the trend can be seen in Figure 14.

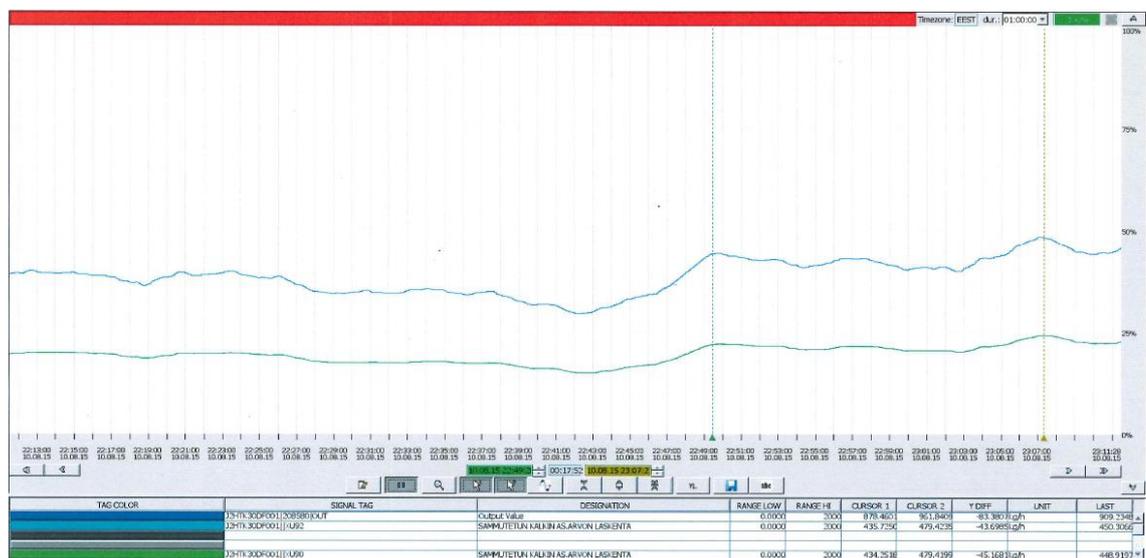


Figure 14. Hydrated lime injection set point and injection screw signals as a function of time

From Figure 14 it can be seen that the two feed screws' sum up to a value really close to the set point. The blue top line represents the set point and the green line below represents one feed screw covering the other, because their values are in practice identical.

Thus inconsistency between injection set point and the realized injection screw signal could not be the reason for the simulation in-accuracy. After double checking all the calculations multiple times it was concluded that the documentation about the control loop had to be documented inadequately and it should be studied more with the help of an automation expert to find out how the loop is actually constructed.

The lime injection measurement signal is calculated from the capacity of the feeding screw and the power it is run on. It is thus possible that the conveying screw is not properly calibrated. The lime injection signal was compared to the hydrated lime silo mass measurement. A time interval where the slaker was not filling the silo and both lines were operating steadily was found for this purpose. Between 29.2. 12:30 and 3.3. 0:00 the silo's weight measurement showed a 21,630 tons decrease while the hydrated lime injection screw measurements summed up to 25,324 tons. According to this calculation the lime injection screw signal is roughly 17 % higher than silo weight measurement.

During year 2015 a total of 2187,17 tons of CaO and 1991,2 tons of Ca(OH)<sub>2</sub> were consumed (if lime slaker is not in operation, hydrated lime is delivered to the site as such). Total hydrated lime consumption from the year 2015 could be calculated by combining the CaO-consumption multiplied by CaO → Ca(OH)<sub>2</sub> production coefficient calculated earlier (1,321) with Ca(OH)<sub>2</sub> –consumption. The quality (Ca(OH)<sub>2</sub> content) of hydrated lime is assumed to be 100 % in these rough calculations, but in reality it is un-likely that all of CaO would react to form hydrated lime.

$$1,321 * 2187,17 t + 1991,2 t = 4880,5 t$$

When the total hydrated lime consumption as reported in last year's yearly report was divided by hours of operation of both lines, the following average consumption was obtained:

$$\frac{4880,5 t}{(7977 + 7709)h} = 311 \frac{kg}{h}$$

This is quite close to the design value of 329 kg/h by LAB (can be seen in Table 13), but more than average of lime injection screw measurement values.

Table 13. Utility reactants design consumptions at 110 % load [25]

UTILITY REACTANTS						
Designation		CaO 95% For 2 lines	Ca(OH) <sub>2</sub> To injection #1 of each line	Ca(OH) <sub>2</sub> To injection #2 of each line	ACTIVATED CARBON For 2 lines	ACTIVATED CARBON For 1 line
References		4	5.1a ; 5.2a	5.1b ; 5.2b	6	6.1 ; 6.2
Flow Rate	kg/h	511	329	0	16,0	8,0
	m <sup>3</sup> /h	0,57	0,73	0,00	0,04	0,02
H <sub>2</sub> O	kg/h	/	/	/	/	/
Temperature	°C	ambient	ambient	ambient	ambient	ambient
Pressure	barg	/	/	/	/	/
Density	kg/m <sup>3</sup>	900	450	450	450	450

The different possible ways to estimate hydrated lime consumption give a wide range of different results. The consumption of lime in the yearly report is measured by the truck weighing scales at the gate, silo weight change by weighing device in the silo and lime injection signal by a calculation done based on the conveying screws capacity. The different results are inconsistent; the highest obtained value is the average consumption calculated by the yearly consumption, the average calculated from the injection screw data is almost 20 % lower but the silo level measurement indicates that the actual consumption would be lower than what the injection screw indicates.

### 5.3.3 Flow rate and reaction time

The operation range at LAB-LOOP's inlet is set to be 70 250-131 889 Nm<sup>3</sup>/h and extreme maximum flow 145 055 Nm<sup>3</sup>/h. Calculated from the flue gas flow data by extracting reagents boosting air the results and 120 % flue gas flow estimations can be seen in Table 14.

Table 14. Flue gas flow ranges at LAB-LOOP inlet

110 % flue gas flow at LAB-LOOP inlet		120 % flue gas flow at LAB-LOOP inlet (estimation)	
Minimum	99 700 Nm <sup>3</sup> /h	Minimum	109 000 Nm <sup>3</sup> /h
Maximum	153 800 Nm <sup>3</sup> /h	Maximum	168 000 Nm <sup>3</sup> /h
Average	131 300 Nm <sup>3</sup> /h	Average	143 500 Nm <sup>3</sup> /h

It turned out that reagents injection air is controlled by operators through DCS using a percentage of maximum and that there is no measurement data of it, it can be assumed that it doesn't depend linearly on the flue gas flow rate. Thus the best estimation available (2400 Nm<sup>3</sup>/h) was used for both 110 % and 120 % load calculations. The bag filters' de-

clogging air pulses should also be extracted from the flow signal data, but since the flow increase caused by the pulses is so small, it can be neglected in these estimations.

Maximum flow under 110 % load and steady operation has already exceeded the extreme operation limit value of LAB-LOOP. Average flow has barely remained inside the operation range of 70 250-131 889 Nm<sup>3</sup>/h. The average estimated flue gas flow under 120 % would be below extreme limit value but peaks would be significantly above it.

Since most of the reactions with pollutants and the reactants take place at the surface of bag filters, it is not necessary to study the reactions time inside the LAB-LOOP and the increasing velocity. The absorbent cake forming on the surface of bag filters continues to remove acid compounds [13, 612]. The increasing velocity of flue gas probably would have an increasing effect on the scuffing of the duct.

#### 5.4 Bag filters with residues re-circulation

The neutralized acidic compounds, absorbed heavy metals and particles form a residue powder which is filtered out from the flue gas stream by fabric bag filters. There are 4 cells each containing 360 bags. The residues form a cake on the surface of the filters and most of the chemical reactions between the reagents and the pollutants take place there. A pneumatic de-clogging system is used to control the thickness of the cake. An air pulse is directed to the bag filter from the downstream side and the pressure wave brakes the cake into pieces. The frequency of bag filters' cleaning is controlled by calculated pressure loss over bag filter section. When a maximum pressure loss over bag filters is reached, a cleaning sequence will start to direct air pulses to a row of bag filters at a time. The residues from two (2) chambers fall to separate hoppers and are conveyed to a residue storage silo by a common conveying screw and after that to a pneumatic transportation system. From the pneumatic buffer silo the residues can be directed to either re-circulation silo or to one of four residue collecting silos. A large fraction of the residues is re-circulated back to the reactor to decrease the consumption of reagents [17, 4.2-4.3; 18].

#### 5.4.1 Increased flow rate

Operation range of bag filter house is stated to be 71 450-135 563 Nm<sup>3</sup>/h. Extreme maximum flow limit at bag filter inlet is 148 728 Nm<sup>3</sup>/h and for temperature continuously 160 °C and exceptionally 165 °C [11]. The flue gas flow at the bag filter inlet can be estimated to be the same as DCS's flue gas flow signal before ID fan. Bag filter de-clogging pulses increase the flow and should thus be extracted, but their effect is so small that it is considered to be insignificant. The flow specs can be seen in Table 15.

Table 15. Flue gas flow ranges at bag filter house inlet

<b>110 % flue gas flow at bag filter house inlet</b>		<b>120 % flue gas flow at bag filter house inlet (estimation)</b>	
Minimum	102 100 Nm <sup>3</sup> /h	Minimum	111 400 Nm <sup>3</sup> /h
Maximum	156 200 Nm <sup>3</sup> /h	Maximum	170 400 Nm <sup>3</sup> /h
Average	133 700 Nm <sup>3</sup> /h	Average	145 900 Nm <sup>3</sup> /h

Average flow has been inside operation range of bag filters but the peak flow has exceeded extreme maximum limit. Estimated average flow at 120 % load would be above operation range but below extreme maximum limit.

#### 5.4.2 Declogging

When the absorbent cake on top of the filter grows, the pressure drop increases and at some point the formed cake has to be removed [16, 89]. It is likely that under the desired 120 % load the frequency of pneumatic declogging will increase, since the amount of injected lime and the particles per time will increase. Figure 15 presents the declogging pulses for each of four chambers for one line during 24 hours.

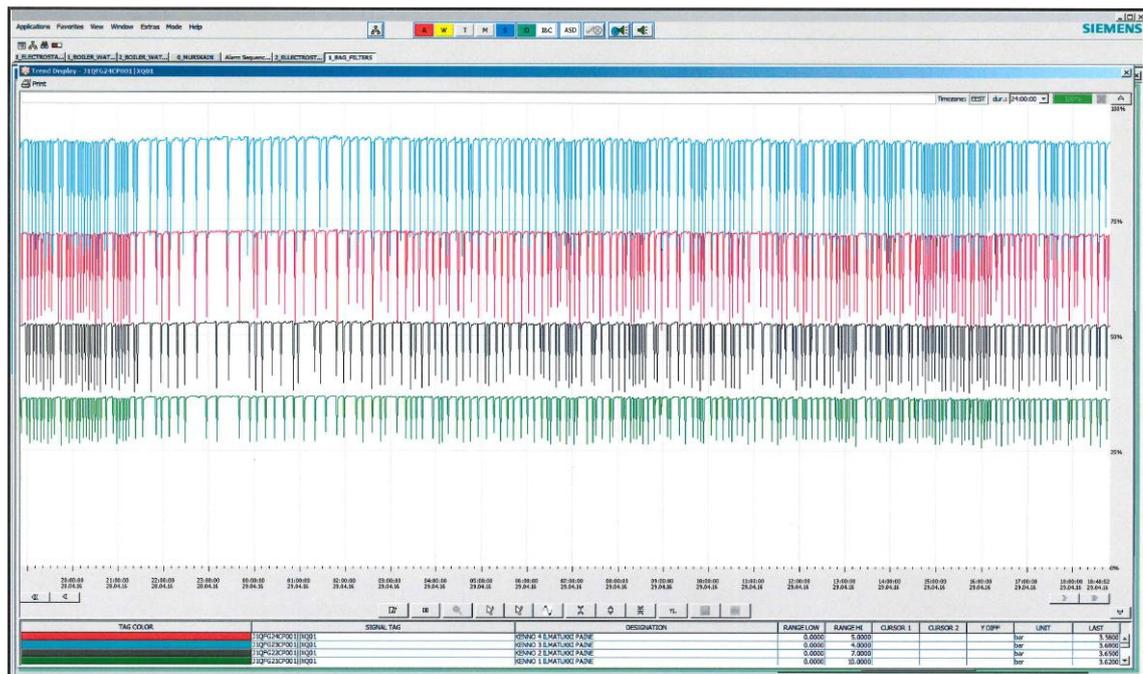


Figure 15. Bag filter de-clogging pulses during 24 hours

The pulse frequency varies from 3 to 13 per hour. Since the data is only from one day, it can only give a rough idea about how frequent the de-clogging pulses are. During the most frequent pulses there is over 4,5 minutes in between pulses. Before the next pulse, the pressurized air vessel has to be filled/pressurized again. No precise information about how frequent the pulses can be found, but probably the restricting factor is automation, not the physical loading of the vessel.

In addition to the increased need for de-clogging and pressure drop, the increased load might decrease the filters' service life. The bags' life span decreases as the flue gas flow rate divided by the collection area increases [13, 608].

#### 5.4.3 Contaminated ash re-circulation

According to the design mass balance data sheet (Table , the reference residue production from two bag filter chambers is 6141 kg/h, so for one line it is then 12 282 kg/h. Residues re-circulation is supposed to be 11 803 kg/h for one line. Residue flow to silo from two lines is stated to be 958 kg/h.

Table 16. Residue production and re-circulation at MCR [25]

RESIDUES						
Designation		Residues under 2 bag filter cells	Residues recirculation	Bag Filter residues from 2 lines to storage silo	Fly ash under 1 ESP	Total ash to storage silo (boiler ash included)
References		7.1a ; 7.1b ; 7.2a ; 7.2b	8.1	9	10.1	11
Flow Rate	kg/h	6141	11803	958	296	812
Temperature	°C	134	134	134	215	215
Density	kg/m <sup>3</sup>	600	600	600	700	700
<i>Composition</i>						
Dust	kg/h	361	695	56	296	812
CaCl <sub>2</sub>	kg/h	2475	4757	386	-	-
CaSO <sub>4</sub>	kg/h	898	1725	140	-	-
CaF <sub>2</sub>	kg/h	43,4	83,5	7	-	-
Ca(OH) <sub>2</sub>	kg/h	1446	2779	226	-	-
CaCO <sub>3</sub>	kg/h	651	1252	102	-	-
Impurity	kg/h	164	314	25,5	-	-
Activated carbon	kg/h	103	197	16,0	-	-

The ratio of residues directed to end silo to that directed to re-circulation is  $479/11803 = 0,04 = 4\%$  by design. In practice this is applied by filling the conveyor silo for 420 seconds a time (shorter times are possible if level alarm is reached) and then sending the residue to re-circulation 9 times in a row and then once to end silo. This is the default sequence, but in practice more residue will be directed to end silo if there are fault situations.

The re-circulated residues are humidified by the means of process steam extracted from steam turbine. There is one residue silo for each line. Density of contaminated ash is stated to be  $600 \text{ kg/m}^3$  [25].

It proved to be really hard to obtain reliable data about residues' production and re-circulation. There is a signal measuring residue re-circulation in kg/h. Maximum value found from the steady operation periods was 3109 kg/h. The re-circulation screw had been off for 2,4 % of measured times. Since the design value for residue re-circulation is 11 803 kg/h, the measurement of the screw had to be studied further. It turned out that the screw is not tightly fitted, which means that residues can escape the flaps of the screw. This is a problem especially because the screw conveys residues forward from a buffer silo which receives badges of residue by the means of pressure. The pressure will then push residues past the screw, resulting in a highly un-reliable measurement. Thus information about re-circulation rates and their variation couldn't be attained.

Total amount of ash production can be seen from Vantaa Energy's yearly environment report. Total amounts of produced ashes were 4 096 tons of fly ash and 8 415 tons of

contaminated ash [9]. By dividing with the operation times we get the average production per hour for one line:

$$\frac{4\,096\,000\text{ kg}}{(7709 + 7977)h} = 261,1 \frac{\text{kg}}{h}$$

$$\frac{8\,415\,000\text{ kg}}{(7709 + 7977)h} = 536,5 \frac{\text{kg}}{h}$$

As can be seen in Table 16 fly ash to silo production is designed to be 406 kg/h for one line and contaminated ash 958 kg/h per line → 479 kg/h per line summing up to 885 kg/h. The realized productions of fly ash and contaminated ash sum up to 797,6 kg/h. Some ash will be collected below cooling tower, but there is no measuring signal for it in the automation system. This means that the total amount of produced ash is quite close to the design values, but it is distributed differently throughout the system, since less ash is being collected in the ESP and correspondingly more in the fabric filters. Handling of contaminated ash is a more expensive service for Vantaa Energy.

#### 5.4.4 Contaminated ash transport and storage system

Information of the size of the residue silos couldn't be found either in documentation or on site. The capacity of the silos was estimated by studying their emptying intervals during one month. Level measurements from all ash silos can be seen in Figure 16.

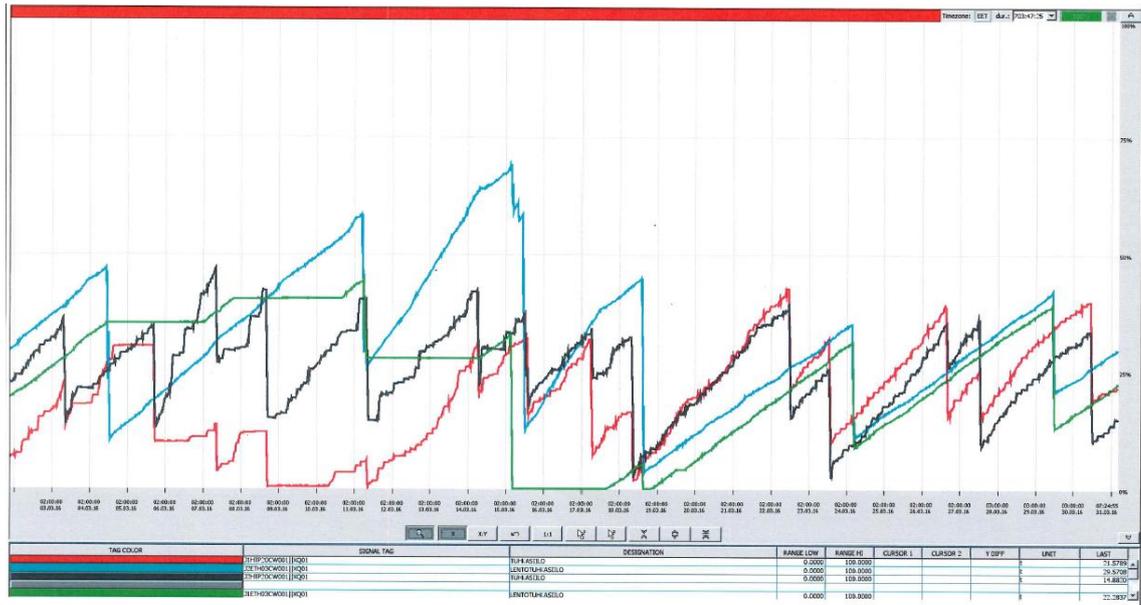


Figure 16. Ash silo levels during one month

Red and black lines depict contaminated ash silo levels. From Figure 16 we can see that both silos were emptied 14 times. Their size is similar to fly ash silos, but as can be seen in Figure 16, contaminated ash silos were emptied more frequently than fly ash silos, because contaminated ash production has been higher than fly ash production. Increased emptying frequency would not be a problem while operating the plant at 120 %, because closed vessel trucks can be ordered on site whenever needed.

The automation sequence behind pneumatic transportation of ashes should be studied in more detail to know what the limitations of the system are when it comes to the conveying system. However it is known that if the buffer silos for contaminated ash fill faster than the time that is set for their emptying frequency, the automation system will stop filling and perform emptying faster, so the conveying system doesn't set any evident limitations for an increased contaminated ash production. Because ESP's efficiency is not on the required level, contaminated ash production has been higher than designed from the beginning. If ESP's efficiency can be improved, it might even out the increased contaminated ash production.

If we conditions [13, 341]. assume that contaminated ash production will increase when thermal load is increased, it will create additional costs even if it will not cause technical problems due to ash handling fees. The increased costs should be considered while estimating the viability of the load shift.

## 5.5 Induced draft fan

The induced draft (ID) fan draws the flue gas from the furnace by creating necessary under pressure. The fans in the plant in question have two motors operating simultaneously. The fan is designed for a maximum capacity of 156 000 Nm<sup>3</sup>/h (wet). The fan is driven by 2 motors each motor providing 50 % of the total maximum necessary power and allows operating the furnace at the nominal load in case of failure of the other motor [17, 4.2].

### 5.5.1 Flow rate change

As described earlier during September 2015 – March 2016 the average and peak maximum flue gas flow measurement at ID fan inlet have been 133 700 and 156 200 Nm<sup>3</sup>/h respectively under 110 % load. Flue gas flow ranges can be seen in Table 17.

Table 17. Flue gas flow rates at ID fan inlet

110 % load at inlet ID fan		120 % load estimation at inlet ID fan	
Minimum	102 100 m <sup>3</sup> /h	Minimum	111 400m <sup>3</sup> /h
Maximum	156 200 m <sup>3</sup> /h	Maximum	170 400 m <sup>3</sup> /h
Average	133 700 m <sup>3</sup> /h	Average	145 900 m <sup>3</sup> /h

The fan is designed for a maximum capacity of 156 000 Nm<sup>3</sup>/h (wet), which means that it is operating under maximum design load already at 110% load steady operation peak moments. The estimated average flow of 145 900 m<sup>3</sup>/h under 120 % load is still inside the fan's operating range, but the estimated peak maximum of 170 400 m<sup>3</sup>/h is roughly 17% over the design capacity.

### 5.5.2 Behaviour of suction pressure and vibrations

Flue gas fans' operation is controlled by a set point of -1,2 mbar for pressure inside the furnace. If this demand for under pressure cannot be met, the boiler cannot combust waste completely enough and will be run down [15]. All the devices in between the fans and the boilers will increase the pressure difference that the fans need to produce due to resistance to flow because of friction in different structures. The biggest sources of increase in pressure difference are the bag filters, cooling tower and economizer [15].

There is a maximum limit of -75 mbar pressure measurement before the stack. If the under pressure created by the ID fan reaches this limit, the fan will be run down. In Figures 17 and 18 the pressure before ID fan is plotted against flue gas flow measurement at 110 %.

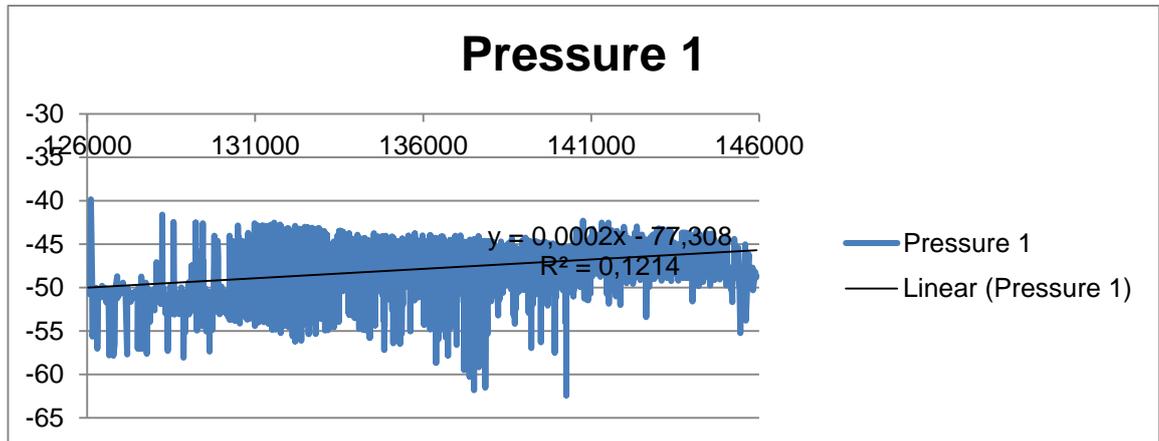


Figure 17. Pressure (mbar) before ID fan plotted as a function of flue gas flow rate (Nm<sup>3</sup>/h) in line 1

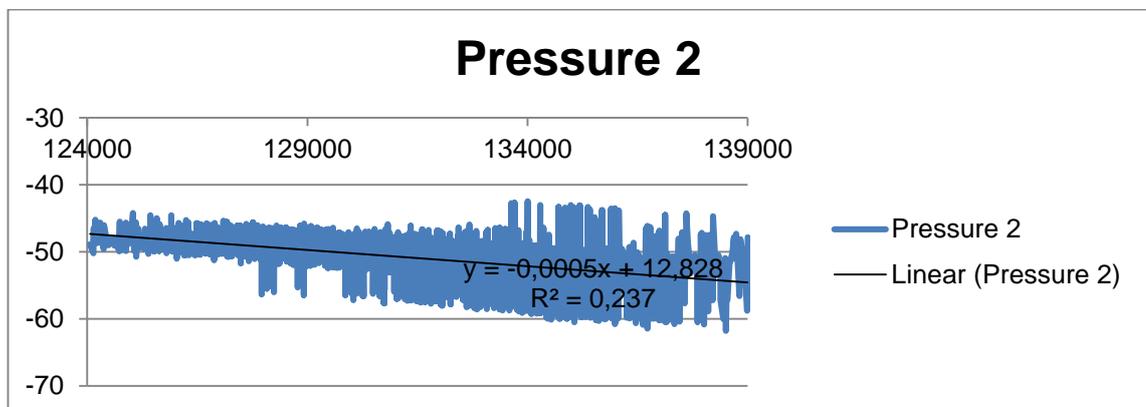


Figure 18. Pressure (mbar) before ID fan plotted as a function of flue gas flow rate (Nm<sup>3</sup>/h) in line 2

It is impossible to say anything about the pressure created by the ID fan as a function of flue gas flow rate. The lines show an opposite trend both having a really poor R<sup>2</sup>-value. R<sup>2</sup>-value is a statistical tool that describes how well your model fits your data. R<sup>2</sup> is always between zero and one, zero representing that the model explains 0 % of the variability of the data around its mean and one that the model explains 100 % of it. Of course a truly high R<sup>2</sup> -value could not be expected from a model that so strongly simplifies a complicated phenomenon. Obviously there are other parameters that have an effect on

the required total pressure difference to keep the boilers at a sufficient under pressure. Probably lime injection and ash and pollutant concentrations have a significant effect on the needed pressure difference. For the pollutant concentration and thus lime injection nothing can be done, since the composition of waste varies greatly and pollution limit values cannot be exceeded. One thing that could be changed is the ash content of flue gas by increasing the poor efficiency of ESP. Unfortunately the data about dust measurement after ESP is not reliable since the sensor has been broken most of the time. Since data about lime injection was available, pressure before ID fan could be plotted against lime injection and can be seen in Figure 19.

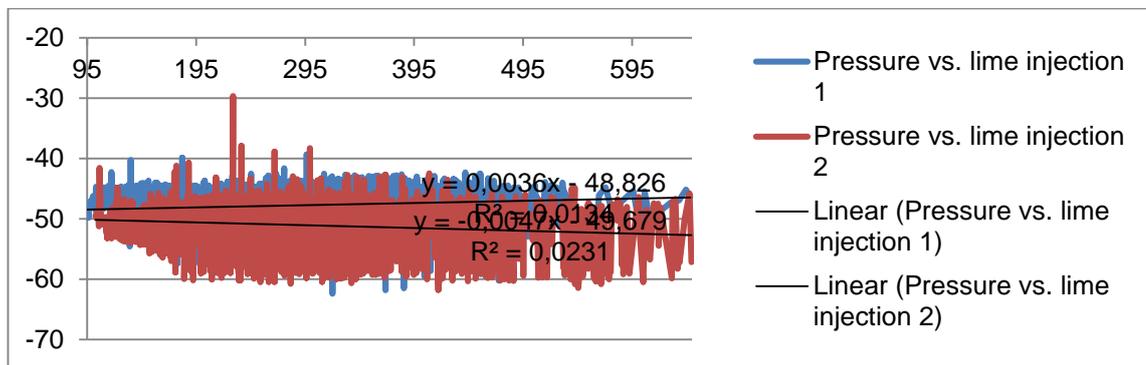


Figure 19. Pressure difference (mbar) plotted as a function of lime injection rate (kg/h)

Plotting the total pressure created by ID fan as a function of lime injection also gives contrary and poor results of correlation.  $R^2$  -values being 0,0134 and 0,0231 the lime injection explains the behaviour of the pressure created by fan even worse than flue gas flow, which is understandable since lime injection has an effect on the pressure difference of LAB-LOOP and bag filters only, while flue gas flow has an effect on the whole system.

It would have been of interest to study the suction pressure of ID fans as a function of re-circulated residues, but as described earlier it was found that reliable data about amount of re-circulated residues at different times couldn't be obtained. The only signal describing it in DCS is a calculated signal using the rotation frequency of the injection screw. As the data of the screw behaviour was studied it was found that the re-circulation flow was only ~10 % of the designed rate. The suspected reason is that the conveying screw is not tightly fitted, which means that residues can escape the flaps of the screw. This is a problem especially because the screw conveys residues from a buffer silo, which receives badges of residue by the means of pneumatic pressure. The pressure pushes residues forward by the screw.

There is also a vibration limit value of 11,2 mm/s for the fans. The behaviour of the vibration as a function of flue gas flow was plotted. Both lines showed negative trend for increasing flue gas flow but the  $R^2$  values were also really poor. Figure 20 shows vibrations of both lines plotted as a function of flue gas flow.

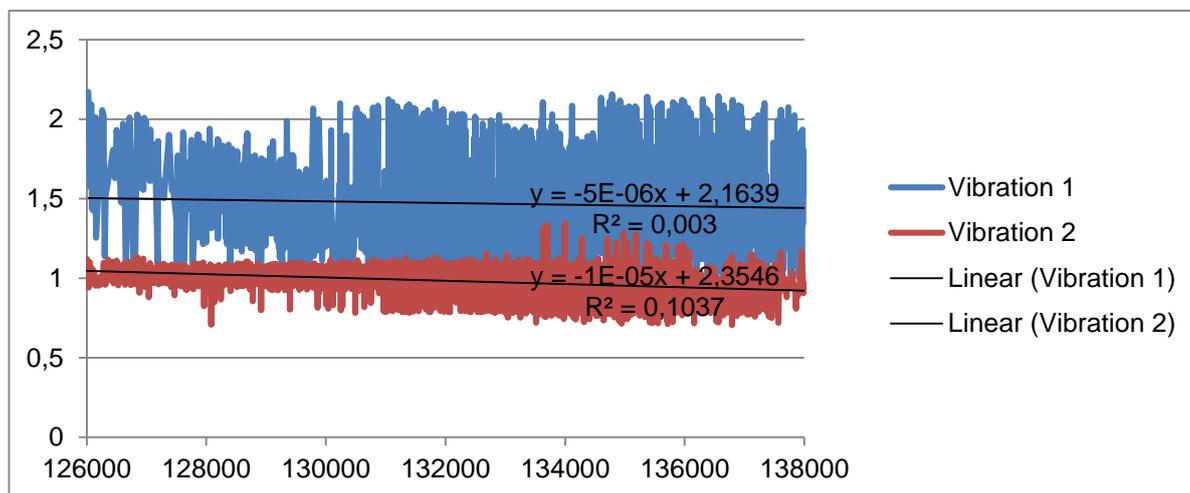


Figure 20. Vibration measurement (mm/s) plotted as a function of flue gas flow rate ( $\text{Nm}^3/\text{h}$ )

It is noteworthy that the vibrations of line 1 fan have been more variant and higher than those of line 2 during the studied intervals.

### 5.5.3 Collapse situations

As the data used to analyse most of other process parameters in this thesis only covers steady operation conditions, another way of studying data of ID fan collapse conditions had to be chosen. The behaviour of the fan in collapse situations was studied by plotting flue gas and flue gas re-circulation flows, pressure before condenser, pressure difference over bag filters, fan vibrations, residue re-circulation silo level and fan motor power on the same figure using DCS's user interface. This way the collapses could be spotted from the plot and then reasons for collapses (pressure max limit or vibration max limit) could be studied and also compared to the flue gas flow and other parameters at that moment. There have been some problems with flue gas re-circulation fan and also the residue re-circulation silo [15, 22] and thus it was also of interest to see how those parameters have affected the flue gas flow and ID-fan.

By studying the ID fan collapse situations a total of 22 collapse situations were found during the studied time period (September 2015-March 2016) out of which 15 involved exceeding vibration or pressure limit. Operator's daily reports were also studied for the days of the collapses. The occurrences are listed with rough flue gas flow level and operators' comments (in brackets) in Appendix 1.

By studying the collapse situations it was learned that vaulting and residue re-circulation buffer silo un-steady operation are considered to be most common reasons for fan collapses. Of course these are personal interpretations of situations and sometimes it might be difficult to say with certainty what caused a collapse and it can also be an unfortunate co-incidence of many things.

## 5.6 Stack

The present stacks have proved to be of in-sufficient quality. Already after one year of continuous operation they showed severe signs of corrosion. It was decided that the stacks will be replaced with new ones made out of a more resilient material. The new material is a stainless steel material called 'Forta SDX 2507' which is usually used in extremely corrosive environments [26]. Because the first stacks proved to be so sensitive to corrosion, the new stacks were chosen to be more resilient than they are required to be according to calculations.

The stacks have a height of 70 meters and the inner diameter is 180 cm. The previous stack had extreme temperature limits of 175 °C as a continuous condition and 180 °C for exceptional conditions [11]. According to LAB's contract the sizing of the stack gives a medium flue gas velocity at nominal (100 %) load [17, 4.2].

Data of flue gas velocity and temperature during steady operations was extracted from DCS. In addition to that the flue gas flow was calculated based on the velocity data and the same temperature related correction factor for STP conversion that is used in the calculations for the wet flue gas flow before ID fans. The flue gas flow is not the same as before the ID fan (where there is a calculated signal) due to flue gas condenser's decreasing effect on the flow after ID fan. Also estimations of flue gas flow under 120 % load were made assuming that flue gas condenser's efficiency would remain on the same level after load shift. Summary of these measurements/calculations can be seen in Table 18.

Table 18. Flue gas characteristics at stack

<b>Parameter</b>	<b>Min</b>	<b>Average</b>	<b>Peak</b>
Temperature(110%)	40,2 ° C	50,1 ° C	147,2 ° C
Velocity(110%)	11,4 m/s	24,7 m/s	15,7 m/s
Flue gas flow(110%)	89 500 m <sup>3</sup> /h	121 200 m <sup>3</sup> /h	147 600 m <sup>3</sup> /h
Flue gas flow(120%)		132 200 m <sup>3</sup> /h	161 000 m <sup>3</sup> /h

Average and maximum flue gas flow before ID fan were 121 200 Nm<sup>3</sup>/h and 147 600 Nm<sup>3</sup>/h respectively. If flue gas condenser is not in operation during high flow periods, the peak flow would increase from this estimation. The peak temperature might also increase if the load shift would have an increasing effect on the flue gas temperature.

On average flue gas flow at stack has been inside the operation range of 72 165-136 918 m<sup>3</sup>/h given for the stack. The peak flow has been above the operation range but below the extreme maximum limit of 156 000 Nm<sup>3</sup>/h. Temperature hasn't reached the extreme maximum continuous or exceptional limits of 175 and 180 °C. Estimated average flow under increased load would also remain inside operation range but peaks might exceed the extreme maximum limit.

## 5.7 Emissions

There are seven emission compounds that the plant monitors continuously. For these emissions the plant has limit values (in mg/m<sup>3</sup>, for dry gas with O<sub>2</sub> 11 %) in accordance with the European Parliament directive on the incineration of waste [27]. The limit values and measured average emissions from yearly environmental report of 2015 have been combined in the Table 19 for comparison.

Table 19. Emission limit values of the plant and realized averages form year 2015 [9]

<b>Pollutant</b>	<b>Limit 24h</b>	<b>Limit 30 min</b>	<b>Realization 2015 lines 1 and 2</b>	
PM	10	30	0,17	0,81
TOC	10	20	1,63	0,89
HCl	10	60	3,41	4,76
HF	1	4	0,08	-0,06
SO <sub>2</sub>	50	200	3,73	13,15
NO <sub>x</sub>	200	400	174,74	175,34
CO	50	100	19,65	8,29

If the flue gas cleaning equipment proves to be sufficient for the desired load, there is no reason to assume that these emission concentrations in effluent gas would change. As can be seen from the table, emissions of most continuously monitored pollutants are on a relatively low level, from 2 % to 40 % of the limit. NO<sub>x</sub> compounds are an exception with a slightly less than 90 % of the limit. This is mostly due to economic decisions, and the capacity of NO<sub>x</sub> –removal is designed to give roughly 100 mg/m<sup>3</sup> concentration as a result. From this point of view even if flue gas cleaning would prove to be in-sufficient for some pollutant compound, it would not mean exceeding of limit values.

If flue gas cleaning equipment proves to be sufficient for desired 120 % load, the pollutant concentrations in effluent gas will not change, but the absolute amount of pollutant compounds being discharged to the surroundings per unit time will increase. The total amounts of emissions in kilograms can be found in the yearly environment report. Assuming that the concentrations of pollutants stay the same, that the plant has been operated almost 100 % of the time at 110 % during year 2015 and that flue gas cleaning capacity is sufficient for 120 %, then the amount of pollution in kilograms under 120 % load can be estimated by simply multiplying with the same ratio as with what the flue gas production was estimated with. Realized pollutant emissions and 120 % estimations can be seen in Table 20.

Table 20. Pollutant emissions realized during 2015 and estimation for 120 % load

<b>Pollutant</b>	<b>Year 2015 (kg per lines 1 and 2)</b>		<b>Year 2015 (kg total)</b>	<b>120% estimated (kg total)</b>
PM	186	857	1 043	1 138
TOC	1 017	41	1 058	1 154
HCl	1 577	1 476	3 053	3 331
HF	16	2	18	20
SO <sub>2</sub>	1 617	4 940	6 557	7 153
NO <sub>x</sub>	184 612	179 217	363 829	396 904
CO	13 462	5 131	18 593	20 283

Engineering company Pöyry made a fallout simulation for combined transportation and combustion emissions at the design phase of the plant. The fallout model showed that W-t-E plant's emissions' fallout would remain far below the exposure limits for the surrounding residential and natural areas even with the maximum allowed emissions. For example combined combustion and transportation emissions from the plant to the surroundings are in a range of 1-2 % of the other transportation emissions in the area [28]. In other words increasing emissions would create no hazard to the environment as long as limit values are not exceeded. It is important that limits are not exceeded also because it means that the process has to be run down, and it is really expensive for the company.

During year 2015 seven (7) occasions of exceeding emission limit values were reported. Six (6) of these occurrences were exceeding CO limit value. CO is a pollutant that forms during incomplete combustion and is thus the result of problems inside the boiler. The remaining event was exceeding SO<sub>2</sub> 30 minute limit value. According to the yearly report, exceeding the SO<sub>2</sub> limit value happened due to high concentrations of sulfur and chloride in the waste. Lime injection rate was at its maximum but it wasn't sufficient to bind all of SO<sub>2</sub>. The solution to the situation was to decrease thermal load of boiler [9]. This means that already at 110 % load there has been a situation when the flue gas cleaning system performance was inadequate. The probability of similar occurrences increases with the flue gas flow increase since increasing flue gas flow has an increasing effect on the pollutant amounts per time and lime injection. On the other hand since municipal mixed waste composition might vary greatly, sometimes the sulfur and chlorine content might be so high, that it's impossible to prevent exceeding emission limits.

The lime injection rate was studied at the time of exceeding the SO<sub>2</sub> limit value. The occurrence was reported on 31.8.2015 between 22:00-23:00. Figure depicts lime injection screw signal from 21:00 to 0:00.

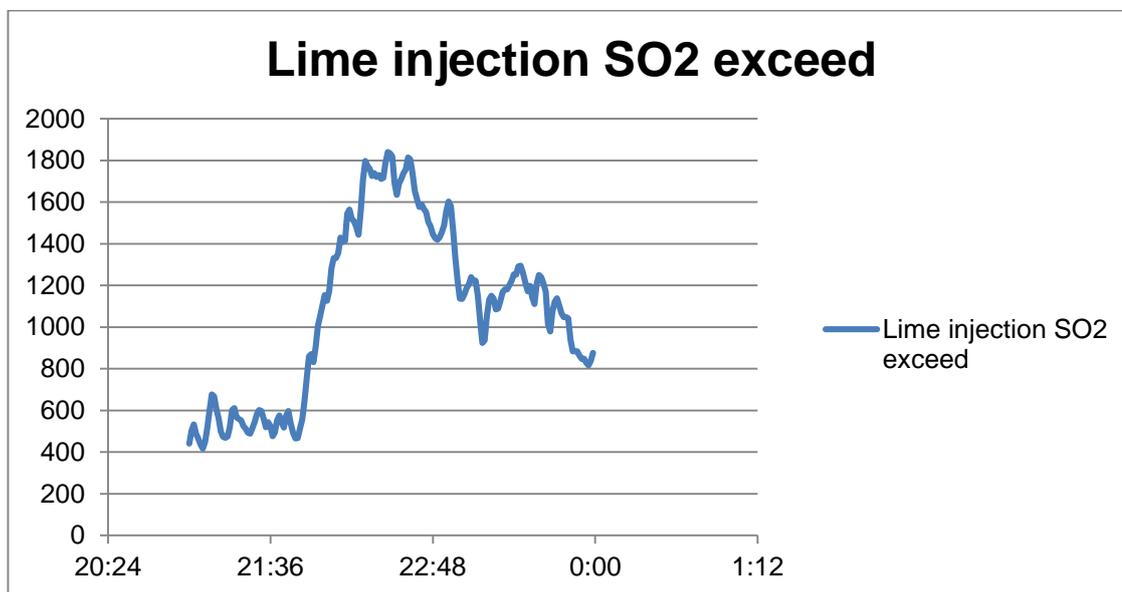


Figure 21. Lime injection rate (kg/h) during exceeding the limit value of SO<sub>2</sub>

Maximum lime injection according to conveying screw data was 1841,2 kg/h. According to LAB's documentation the maximum capacity of lime injection should be 2200 kg/h. So either the conveying screw wasn't fast enough to keep up with what was demanded by the system or the system failed to demand enough of lime. Without further investigation and calibration of the screw it is impossible to know what the reality is.

CO<sub>2</sub>-emissions will increase at the same rate as fuel consumption. Total of CO<sub>2</sub>-emissions during year 2015 was 146 837 tons. If the thermal load distribution and availability of boilers remain at the same level than year 2015 (93,1 %), this means simply an increased level of roughly  $(120/110) * 146\ 837\ t = 160\ 186\ t$ .

If availability improves to for example the guaranteed availability of 96,1 %, then CO<sub>2</sub>-emissions would rise to  $146\ 837\ t / (7977+7709)h * (2*(8760-336)h * 0,961 * (120/110)) = 165\ 342\ t$ .

Economically carbon emissions will not have an effect on Vantaa Energy because municipal waste is not included in the carbon trade system.

Amount of produced slag (bottom ash) would also increase. This also has no economic significance because slag handling creates no costs for Vantaa Energy.

## 6 Discussion and conclusions

As a summary, operation ranges and the flue gas flow specs and estimations, all in Nm<sup>3</sup>/h, can be seen in Table 21.

Table 21. Equipment operation ranges and flue gas flows

Process point(in-let)	Operation range	Extreme flow limit	Average 110 %	Peak 110 %	Average 120 %	Peak 120 %
ESP	80 000-145 000	159 500	143 100	169 500	156 100	184 900
Cooling tower	70 000-130 000	143 000	129 900	152 400	141 800	166 300
LAB-LOOP	70 250-131 889	145 055	131 300	153 800	143 500	168 000
Bag filter house	71 450-135 563	148 728	133 700	156 200	145 900	170 400
ID fan	72 165-136 918	156 000*	133 700	156 200	145 900	170 400
Stack	72 165-136 918	156 000*	121 200	147 600	132 200	161 000

Average flow rates at different process points have stayed inside normal operation ranges. All steady operation peaks have exceeded the extreme flow limits of process equipment except for the stack. All estimated 120 % average flow rates remain below extreme operation limits. It can be said with certainty that the occurrences of exceeding extreme operation limits would become more frequent for the whole process.

The amounts of observations above equipment operational range and extreme maximum were calculated both at 110% load and at estimated load of 120% and they can be seen in Table 22.

Table 22. Percentages of range exceeding observations

Process point (inlet)	110% load, % of observations above operation range / extreme limit		120% load, % of estimated ob- servations above operation range / extreme limit	
ESP	41,9	0,4	92,9	34,7
Cooling tower	46,8	0,4	99,8	35,5
LAB-LOOP	41,6	0,3	99,8	32,5
Bag filter house	29,0	0,2	99,5	23,0
ID fan	19,4	0,0	98,5	4,1
Stack	4,4	0,0	10,1	0,7

Temperature data from before cooling tower shows that the maximum temperature during steady operation has been 147 °C and decreasing over the studied 7 months. The temperature range is below Hitachi's design temperature range. Extreme temperature limit for cooling tower is 165 °C. Therefore, it seems that flue gas temperature increase due to increased load would not be a problem for the equipment, at least not mechanically. However, calculations show that under the desired 120 % load cooling tower's capacity would not be sufficient to cool the increased flue gas stream for more than approximately 5 °C. The following process equipment's extreme continuous temperature limit is 160 °C (165 °C exceptional), so even if cooling tower would not cool the flue gas at all, the following equipment could bare the temperature. Insufficient cooling would probably have a negative effect on the reaction rate between reagents and pollutants though.

Activated carbon injection capacity is definitely sufficient for a 120 % load. Different methods of estimating lime consumption resulted in inconsistent results, but what they all have in common is that they indicate a lower than expected consumption. During last year, one exceeding of SO<sub>2</sub> emission limit value occurred. The likelihood of similar events will increase with the possible load shift. The lime injection depends on many parameters, and if the un-favourable conditions happen to occur at the same time, the reagents injection system might fail even under normal loads. For example, efficient mixing of waste becomes more important during higher loads, since it can help prevent exceptionally high pollutant concentrations. It was found that during the exceeding of sulphur dioxide limit value the lime injection screw was not operating on full capacity. Reasons for

this should be detected from the automation system to prevent similar occurrences in the future. The injection screw should also be calibrated because its accuracy is uncertain. It has to be kept in mind that the screw will scuff during its operation hours, and this might affect its capacity. Scuffing will of course increase alongside the increased load.

Reliable data about contaminated ash production and especially re-circulation rates proved to be challenging to find. Only rough average rates could be attained; thus, the variation range remains a mystery. What can be said about contaminated ash production is that on average, it has been produced more than estimated by LAB. The design rate for a 110 % load is 479 kg/h and the production has been 537 kg/h on average. On the other hand, fly ash production design value is 406 kg/h, and average fly ash production during 2015 has been 261 kg/h; thus, fly ash production has been lower than designed. Summed up together the ashes production approaches the summed design value: 885 kg/h by design and 798 kg/h realized. This is logical since it is known that the ESP's are not performing as they should; hence in practice, a fraction of fly ash is collected at the bag filters instead of ESP. The conveying system for fly ash is designed to be far larger than required; thus, low performance of ESP's probably will not become a problem in terms of ash storage, but having a high content of fly ash in flue gas enhances fouling of equipment and thus the pressure loss over the system. The ID fans have already experienced problems due to the total suction pressure exceeding its limit value, and preventing fouling would be highly important if the desired 120 % load will be executed. Residue re-circulation screw seems to be a part of the problem as well. Because the screw is not tight, the buffer silo level behaviour becomes unsteady and might result in rapid fluctuations of pressure difference over bag filters. Alone these things might have only a slight affect but together they build up.

The flow data as such indicates that the real average flow rate has been higher than the design rates. Reasons for this might include vaulting in feed hoppers and leaking process parts, for example the peak lime feeders, which are not tight while not in operation. The effect of the un-sealed peak feeders is minor, but it could be one part of making the load shift more plausible. In situations of vaulting, the flue gas flow might increase momentarily (air leaks to boiler through feed hopper) [15]. It is highly difficult to completely prevent vaulting from happening; thus, it is regarded as a component of normal operational conditions. The flue gas flow data extracted from DCS most probably includes situations of vaulting as well because it is quite common. Vaulting occurrences could be decreased

by intensifying crushing of the fuel waste and visual observation of the waste to prevent large objects from entering the feed hoppers.

## **7 Limitations and need for further study**

### **7.1 Unreliability**

The data processed in this thesis consists of measurements and calculations with dozens of different sensors and approximations. It would be unreasonably tedious to estimate the uncertainty of each DCS signal, and it might not be possible to find this information of all equipment and sensors. There are different standards for measuring devices and the standards have been followed by Vantaa Energy's suppliers, but there is still always error in all measurements and when signals are created from many measurements the error multiplies. The results presented in this thesis should be regarded as rough estimations only because the amount of error cannot be known.

The estimations about flue gas flow under 120 % load have been made assuming that the boilers would cope with the load shift meaning that combustion would be complete enough and, for example air injection capacity would be sufficient. In practice, increasing the load would probably affect flue gas characteristics, for example by increasing temperature and maybe even by relatively decreasing the flow if combustion would not be as complete as under lower loads. The water cleaning system in the boiler increases the flue gas flow by 7500 Nm<sup>3</sup>/h once every 20 h [14, 4.8]. The cleaning is included in the data extracted from DCS and thus also in the estimations of 120 %, but it is hard to predict how much more fouling and cleaning would occur in the boiler. None of these effects could be taken into account since studying the boiler behaviour under an increased load was not in the scope of this thesis. For this reason, also the results should be regarded as rough estimations.

After the latest overhaul, there have been some problems with leaking super heater feed pipes, and it might have had an increasing effect on the flue gas flow. The amount of leaks is not known.

Since the data extracted from DCS mostly consists of measurements from steady operation times, it does not give a fully representative picture of the reality. The data only

represents steady operation intervals. The times of high pollutant concentrations have an increased probability of, for example, ID fan collapses; thus, if all operation times were included, it could increase the average flow. On the other hand, the unsteady operation times also include situations where the load has had to be decreased due to clogging of boiler or some maintenance work, so the average flow might also decrease.

## 7.2 Further study

If the load shift is decided to be executed, the required automation system changes need to be studied. For example, the steam production set point has a maximum of 83 t/h (corresponds to 110 % load.) Other similar restrictions do exist, and they would have to be found and modified.

Other process parts, especially the boiler, are of interest. The boilers' reaction to load shift would affect the flue gas composition and characteristics and thus also the flue gas cleaning system.

Flue gas fans have suffered from multiple collapses due to overall suction pressure exceeding its limit value. Thus, to prevent such incidents in the future, it would be essential to find out which process parameters have an effect on the pressure build up. This could be studied choosing most probable parameters and analysing their affects with a statistical software, such as R. This way the most effective parameters would be known, and thus the possible actions for enabling the load shift could be targeted well.

## References

- 1 Valtioneuvoston asetus kaatopaikoista, 331/2013, § 28.
- 2 Council Directive 1999/31/EC on the Landfill of Waste.
- 3 Helsingin seudun ympäristöpalvelut -kuntayhtymä. Pääkaupunkiseudun kotitalouksien sekajätteen määrä ja laatu vuonna 2013, HSY [Internet]. Helsingin seudun ympäristöpalvelut -kuntayhtymä; 31.12.2012 [15.3.2016]. Available from: [http://www.jly.fi/2\\_2013\\_pks\\_kotitalouksien\\_sekajatteen\\_maaja\\_ja\\_laatu\\_lr.pdf](http://www.jly.fi/2_2013_pks_kotitalouksien_sekajatteen_maaja_ja_laatu_lr.pdf)
- 4 Jätelaitosyhdistys ry. Energiahyödyntäminen Suomessa, Jätelaitosyhdistys ry [Internet]. Jätelaitosyhdistys ry; [4.5.2016]. Available from: <http://www.jly.fi/energia5.php?order=kunta.nimi>
- 5 Laki vesi- ja energiahuollon, liikenteen ja postipalvelujen alalla toimivien yksiköiden hankinnoista, 30.3.2007/349, § 19.
- 6 Lahti Energia Oy. Kymijärvi II:n polttoaine, Lahti Energia Oy [Internet]. Lahti Energia Oy; [15.4.2016]. Available from: <http://www.lahtienergia.fi/lahti-energia/energia-tuotanto/kymijaervi-ii-voimalaitos/polttoaine>
- 7 Statistics Finland. As much as one-half of municipal waste is burned, Statistics Finland [Internet]. Statistics Finland; 1.12.2015 [15.4.2016]. Available from: [http://www.stat.fi/til/jate/2014/jate\\_2014\\_2015-12-01\\_tie\\_001\\_en.html](http://www.stat.fi/til/jate/2014/jate_2014_2015-12-01_tie_001_en.html)
- 8 Tapio Pukkila. Lounais-Suomen jätteet neljään voimalaan hyödynnettäväksi, Yle [Internet]. Yle; 23.1.2014 [24.5.2016]. Available from: [http://yle.fi/uutiset/lounais-suomen\\_jatteet\\_neljaan\\_voimalaan\\_hyodynnettavaksi/7047979](http://yle.fi/uutiset/lounais-suomen_jatteet_neljaan_voimalaan_hyodynnettavaksi/7047979)
- 9 J. Laulajainen. Vuosiraportti 2015. Vantaa Energy Ltd.; 30.1.2016.
- 10 K. Patomeri. Jätevoimala [Presentation]. Vantaa Energy Ltd.; 8.9.2014.
- 11 Hélène de Tarle. Flue gas data sheet [Internal document], LAB S.A. (LAB document reference 11272 EA 00 101 to 108), 1.7.2011 (modified 10.10.2014).
- 12 Roberto Del Oro, Hitachi Zosen-Inova. Interview by phone; 23.3.2016.
- 13 Walter R. Niessen. Combustion and incineration processes: Applications in Environmental Engineering. Fourth Edition. Boca Raton: CRC Press; 2010.
- 14 Hitachi Zosen Inova AG and Vantaa Energy Ltd. Waste Incinerator Plant contract [internal document], 23.5.2011.
- 15 Jari Järvinen, Vantaa Energy Ltd. Interview; 24.2.2016.
- 16 Jes Fenger, Chistian J Tjell. Air Pollution: From a Local to a Global Perspective. RSC Publishing; 13.3.2009.
- 17 LAB S.A. and Vantaa Energy Ltd. Flue Gas Treatment Plant contract [Internal document], 26.5.2011.

- 18 Hélène de Tarle. Training manual [internal document], LAB S.A. (LAB document reference 11272NA00002), 28.6.2013 (modified 3.11.2014).
- 19 Pöyry Finland Oy. Performance tests of the ESP separation efficiency [Internal document], Pöyry Finland Oy (Pöyry document reference 101002713-001-E0002), 31.3.2016.
- 20 Boubiela Moret. Technical instructions: Screw conveyors [Internal document], LAB S.A. (LAB document reference 11272NA17641), 3.9.2014.
- 21 Fabio Kunz. Heat balance sheet, Incineration & Boiler [Internal document], Hitachi Zosen Inova (Hitachi document reference 50006274), 14.2.2012.
- 22 Kari Pulkkinen, Vantaa Energy Ltd. Interview, 17.3.2016.
- 23 Helsingin seudun ympäristöpalvelut -kuntayhtymä . Juomaveden laatu, HSY [Internet]. Helsingin seudun ympäristöpalvelut –kuntayhtymä; 30.5.2016 [28.4.2016]. Available from: <https://www.hsy.fi/fi/asiantuntijalle/vesihuolto/vedenlaatu/Sivut/default.aspx>
- 24 Sonia McCarthy-Baron. Reagents functional analysis [Internal document], LAB S.A. (LAB document reference 11272EA00029), 31.5.2012 (modified 4.9.2014).
- 25 Hélène de Tarle. Mass balance sheet [internal document], LAB S.A. (LAB document reference 11272 EA 00 010), 29.9.2011 (modified 10.10.2014).
- 26 Outokumpu Oy. Stainless Steel Finder, Outokumpu [Internet]. Outokumpu; 2015 [28.4.2016]. Available from: <http://steelfinder.outokumpu.com/properties/Grade-Detail.aspx?OKGrade=2507&Category=Forta>
- 27 Directive on the Incineration of Waste, 2000/76/EC.
- 28 Pääkaupunkiseudun yhteistyövaltuuskunta YTV. YVA-selostus: Päätöt (pages 78-128), Pöyry Finland Oy, October 2007.

**ID fan collapse situations and suggested causes (in brackets)**

- 7.9. 03:00 Line 2 ~130 000 Nm<sup>3</sup>/h, pressure limit exceeded (residue re-circulation rush)
- 9.9. 13:30 Line 2 ~130 000 Nm<sup>3</sup>/h, pressure limit exceeded (vaulting)
- 13.9. 14:30 Line 1 ~150 000 Nm<sup>3</sup>/h, pressure limit exceeded (possibly re-circulation rush or vaulting)
- 14.9. 10:30 Line 2 ~130 000 Nm<sup>3</sup>/h, pressure limit exceeded (no reason reported)
- 20.9. 15:00 Line 2 ~140 000 Nm<sup>3</sup>/h, pressure limit exceeded (vaulting)
- 23.9. 16:00 Line 2 ~150 000 Nm<sup>3</sup>/h, pressure limit exceeded (vaulting)
- 28.9. 04:00 Line 2 ~150 000 Nm<sup>3</sup>/h, pressure limit exceeded (residue re-circulation rush to LAB-LOOP)
- 3.10. 05:00 Line 2 ~135 000 Nm<sup>3</sup>/h, pressure limit exceeded (residue re-circulation rush to LAB-LOOP)
- 4.10. 20:00 Line 2 ~130 000 Nm<sup>3</sup>/h, pressure limit exceeded (to residue re-circulation rush to LAB-LOOP)
- 10.10. 23:00 Line 2 ~140 000 Nm<sup>3</sup>/h, pressure limit exceeded (no reason reported)
- 4.11. 18:00 Line 2 ~145 000 Nm<sup>3</sup>/h, vibrations limit exceeded (no reason reported)
- 6.2. 18:30 Line 2 130 000-150 000 Nm<sup>3</sup>/h (shifts rapidly), vibration limit exceeded (no reason reported)
- 18.2. 19:00 Line 2 ~135 000 Nm<sup>3</sup>/h, vibration limit exceeded (not mentioned at all)
- 6.3. 06:00 Line 2 ~135 000 Nm<sup>3</sup>/h, vibrations limit exceeded (no reason reported)
- 14.3. 10:00 Line 2 ~145 000 Nm<sup>3</sup>/h, pressure limit exceeded (no reason reported)