Final report

1. Project details

Project title	64015-0633
File no.	Combustion Air Humidification at Waste-to-Energy Facilities
Name of the funding scheme	Energiteknologisk Udviklings- og Demonstrations Program (EUDP)
Project managing company / institution	Rambøll Danmark A/S
CVR number (central business register)	35128417
Project partners	Rambøll Danmark A/S, I/S Vestforbrænding, Babcock & Wilcox Vølund A/S, DTU, I/S AffaldPlus, AffaldVarme Aarhus:
Submission date	26 November 2020

2. Summary

The influence of introducing combustion air humidification at line 5 at Vestforbrænding Waste-to-Energy plant (WtE plant) has been evaluated through model calculations, and experimentally by conducting a full-scale measuring campaign. Thermoflex modelling allowing determination of different parameters of the WtE plant and predicting temperatures in the gas and steam circuits, was used to predict effects of water injection in to the furnace with primary air. Selected control system (SRO) data from line 5, Vestforbrænding, have been obtained and analyzed. The selected SRO data sets cover a range of air, gas and steam parameters where we would expect to be able to see possible effects of humidification. The final humidification measurement campaign at Vestforbrænding, line 5, was accomplished in the week of August 10-14, 2020. Combustion air humidification was simulated by injecting water into the LUFO (humidification tests), and the influence on local flue gas temperatures was investigated by conducting suction pyrometer measurements in the furnace/boiler chamber and in the Superheater section, respectively (suction pyrometer measurements). SRO data analysis, fly ash characterization, and visual inspection of the Superheater surfaces was also part of the overall evaluation. To summarize the conducted work with respect to both the modelling and the experiments conducted at Vestforbrænding, then it can be concluded that none of the observed plant operational changes when using steam injection on the level of 7.5 tons per hour at a 25 ton/h (waste input) WtE plant courses concern with respect to daily plant operation. In the study was not observed any problems with respect to boiler chamber temperature, deposit formation, emission levels and ash handling properties. In case water injection is implemented on a WtE plant it would be advisable to implement a control of air supply that is based on the dry flue gas oxygen content, this to ensure that the water injection do not course an unnecessary extra supply of combustion air.

3. Project objectives and implementation

3.1 Project execution

The project was not executed as initially planned as the waste to energy facility Vestforbrænding was not ready to implement the full-scale humidifier as the investment was not viable at this point in time for the facility. The implementation was hence changed from a full scale to a field scale using the air preheater at Vestforbrænding to humidify the combustion air using energy from primarily drum steam. Even though only a fraction of the same humidification could be tested compared with the full scale a number of effects could be tested and some of the technology drawbacks could be tested. Furthermore the technology could prove its viability in a setting where strong focus is on keeping full load and not risking downtime nor any risks to operational personnel. The planned project phases was followed and conducted as described below:

3.1.1 Project definition (WP 1 and 2)

The project was further defined and a plan for the measurement of baselines on the non-modified system was made as in collaboration with all the partners. This is necessary to validate the research results later in the project. A project definition brief will be carried out based on knowledge from existing research and experience from applications with similar features. This is done to create relevant hypothesis as well as suggest which data is needed for the final research plan, measurement equipment specifications and design. The definition period also included a clarification of the appropriate research methods, and to finalize a detailed research plan (WP4). This will contain planning of experiments, modification of measurement equipment and preparation of the measuring campaigns. The clarification of the research methods and baselines will be used to produce design specifications for the later research.

Outcome:

- Delivery 1: Plan for measurements of baselines – See appendix 1
- Delivery 2: Project definition – See appendix 2
- Delivery 3: Elaborate Research Plan – See appendix 1

3.1.2 Implementation (WP3)

The facility itself is supposed to be installed by Vestforbrænding and supplied by B&W Vølund. The implementation in the project wasonly planned to be of monitoring and measurement equipment as well as additional control means at the facility. However, since the full scale was not implemented the implementation was changed to be installation of water spray systems in the combustion air pre-heater. The installation included measurements of water consumption and valves for distribution control. The performance is documented in the performance memo from Vølund and the installation itself is documented in the overall DTU report.

- Delivery 4: Installation of the test systems and equipment

- Delivery 5: CAH Performance – Attachment 3

3.1.3 Research on CAH (WP 4 and 5)

The objective of the research part will be to document and investigate the influence of the humidification process on the waste combustion facility operation. This included full-scale facility measurements with the installed field scale CAH unit.

- Task 1: Measuring campaign 2 “CAH pre-test” and analysis and interpretation results
- Task 3: Measuring campaign 3 “CAH operation” and nalysis and interpretation results
- Delivery 6: Reporting – Attachment 4

4. Project results

4.1 Introduktion

4.2 Research experiments (WP4, 5)

The measuring campaign was be done by simulating the influence of a flue gas humidification unit on the waste boiler performance. The simulation will be done by injecting steam into the primary air thereby increasing the water content in the flue gas, while keeping other operation parameters constant. This will lead to a decreased adiabatic temperature, an increased flue gas flow and increased water content in the flue gas.

4.2.1 Installation and commissioning

The experiments will be conducted on the line 5 waste combustion unit at Vestforbrænding. In practice, the combustion air humidification will be done by injecting water into the LUFO[1] (air pre-heater). A water injection system with nozzles spraying water on the heating tubes inside the LUFO has been installed for this specific purpose.

Vestforbrænding and B&W Vølund managed the installation of the CAH test equipment in the form of water injection nozzles into the LUFO at line 5 at the Vestforbrænding.

Figure 1 Picture of the water injection system installed in the LUFO (right hand side). Black valves for 6 of the lances with nozzles can be seen on pipes on the side of the LUFO.

[1] LUFO: LUftFOrvarmer (Air Pre-heater)

A picture showing the installed water injection system with nozzles spraying water on the heating tubes inside the LUFO is shown in figure 3.1. A rough sketch of the LUFO water injection system is also provided.

Figure 2 Picture of the water injection system installed in the LUFO (look through an inspection port). A lance with three nozzles is spraying water on heating tubes inside the LUFO.

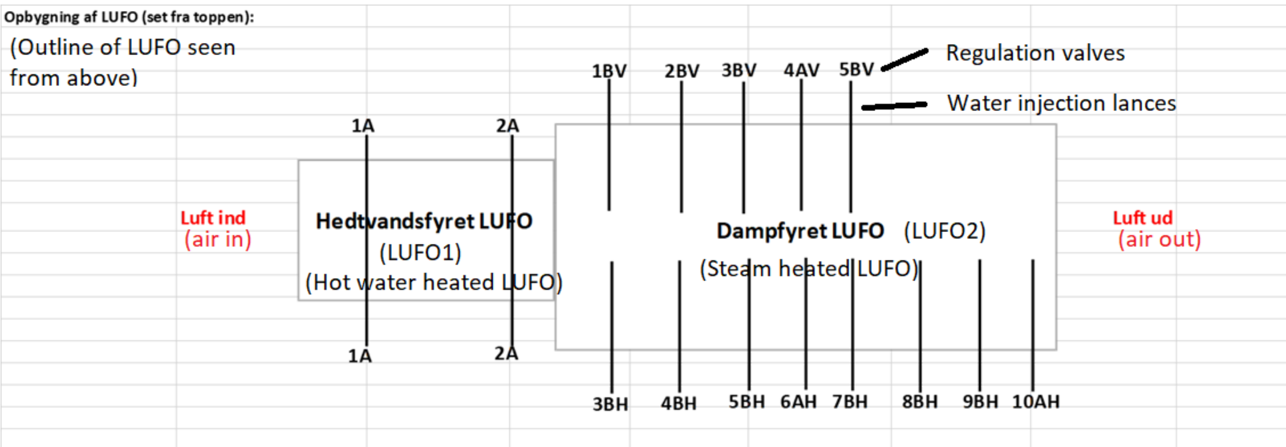

Figure 3 Section drawing of the LUFO system seen from above, with the installed water injection lances and their corresponding regulation valves indicated

4.2.2 Initial modelling and pretest 1

The Thermodynamic modelling concluded that usage of an air humidification system allows increasing the district heating production and effectively utilize the low temperature energy of water vapor condensation from flue gases. Injection of 10 t/h water vapor into the primary air flow increases the maximum district heating system power by 5% in the case of constant fuel consumption and by 6% in the case of constant steam production. Water vapor injection into the primary air flow decreases the temperature of flue gases from the furnace and increases the exhaust gas temperature. Also, the flue gas water concentration increasing make an influence on boiler`s heating surfaces absorption.

The interpretation of the plant data obtained during the humidification pre-test on March 4th, 2020, indicates that we may be able to detect sizeable effects of combustion air humidification, at least on some air and flue gas parameters. Other flue gas parameters may have been affected as well – but the obtained plant data were inconclusive. No negative effects on the production or plant performance were observed. The conclusion was that the setup and CAH effects allowed for the final testing and continues operation of the field scale CAH unit.

4.2.3 Full scale test of continues CAH operation

The final measuring campaign at line 5 at Vestforbrænding has been accomplished in August 2020.

During the measurement campaign, the following measurements have been conducted:

- Local humidity (and temperature) measurements in the primary air before and after the LUFO (to document the efficiency of the water evaporation) has been performed by installing a (hand-held) humidity probe during the tests.
- The effects on local flue gas temperatures in the boiler has been documented by conducting suction pyrometer probe measurements in the furnace/boiler chamber (pos. 9) and in the Superheater section (pos. 2), respectively.
- Collection of SRO data: Effects on plant operation data such as air and flue gas temperatures and flow, steam parameters, and gas emissions (H_2O, O_2, CO_2, CO NO_x and SO_2) has been documented by analysis of relevant SRO data.
- Collection of fly ash samples: Possible negative effects on the fly ash's transport properties has been a concern. Therefore, representative samples of the fly ash have been collected during the tests, and the samples have subsequently been analysed with respect to water content and flow properties.
- Visual inspection of Superheater surfaces by use of camera probe: Video recording of Superheater surfaces were taken through the sampling port at position 2 during the test period - in order to evaluate effects on deposit formation.

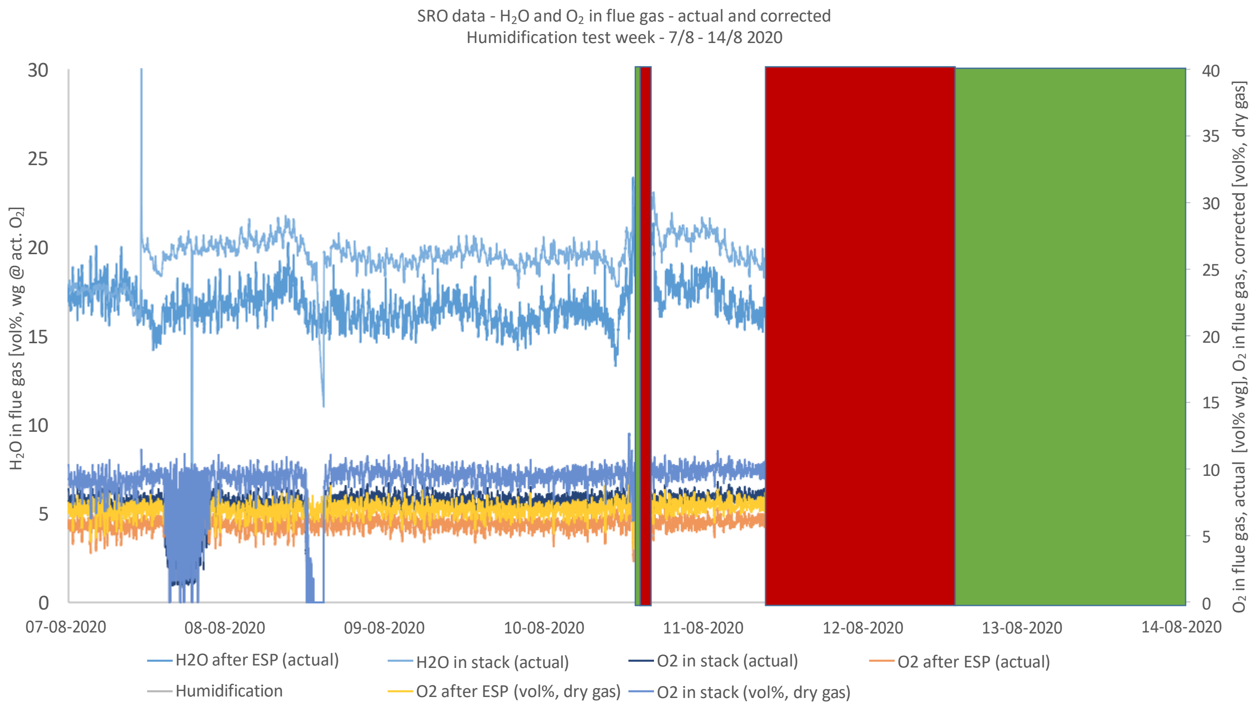

Figure 4 Plant raw data plots of H_2O and O_2 concentrations in flue gas after ESP and in stack, respectively, and O_2 concentrations corrected to dry gas during the week of the measuring campaign. The humidification test periods (red boxes) and reference periods (green boxes) are also indicated

It is concluded based on the experiments with field scale CAH in continues operation that significantly increased water content in the flue gas after the boiler and in the stack could be observed. The extra moisture content amounts to a gas flow of around 11.000 – 13.000 m3/h – or about 6.6 – 7.8 t/h of water evaporated. This is confirmed by measurements in the primary air after the CAH unit that measured approx. 7.5 t/h of evaporated water.

It is concluded that plant was operated at full capacity during the CAH testing and no problems were reported. The plant data confirms that no emission exceeding's or operational parameters were outside normal ranges. It can hence be concluded that the experiments show that CAH with significant amounts of evaporated water into the combustion air can be implemented without negative effects to the operation of a waste-to-energy facility. The energy efficiency of the boiler is slightly decreased during humidification due to the loss of the energy in the added water vapor, this can however be reclaimed in the flue gas condensation unit (this was not in operation during the experiments). The suction pyrometer (and thermoelement) tests confirmed the expectation of not seeing significant changes in boiler temperatures during CAH operation of this magnitude. Testing of the fly ash properties concluded that the fly ash transport properties are not deteriorated due to humidification, it is actually improved.

4.2.4 Overall conclusions

The influence of introducing combustion air humidification at line 5 at Vestforbrænding Waste-to-Energy plant (WTE plant) has been evaluated through model calculations, and experimentally by conducting a full-scale measuring campaign. The line 5 at Vestforbrænding treats typically 25 tons/h of waste and thereby produces 17 MW of power and 82 MW of district heating. The main conclusions from the investigations are summarized below:

Thermoflex modelling, allowing determination of different parameters of the WTE plant and predicting temperature in the gas and steam circuits, was used to predict effects of water injection in to the furnace with primary air of line 5, Vestforbrænding. The model predicted that:

- Injection of 10 t/h of water vapor in the primary air flow decreases the temperature of the flue gases from the furnace and increases the exhaust gas temperature. The maximum temperature effect, in terms of decrease in temperature at 10 t/h water vapor injection, would amount to 40 °C (corresponding to a temperature decrease from 800 °C to 760 °C at the outlet of the furnace chamber).
- Injection of 10 t/h water into the primary air flow increases the maximum district heating system power by 5% relative to the total fuel consumption and by 6% in the case of constant steam production. A small increase of flue gas temperature after the last economizer makes an influence on flue gas specific energy, but the biggest influence on the flue gas energy content is the increased concentration of water in the flue gas.
- The primary and secondary air mass flows grow proportionally to the steam mass flow from air humidification system. Further, in the case of holding constant the O_2 concentration in wet gases the O_2 concentration in the dry flue gas is increased by increasing the primary and secondary air flows.

Selected control system (SRO) data from line 5, Vestforbrænding, have been obtained and analyzed. The selected SRO data sets cover a range of air, gas and steam parameters where we would expect to be able to see possible effects of humidification. The analysis of the SRO data found that:

- On typical plant operation, there are generally large variations when it comes to waste input flow, volumetric flow of primary and secondary air, flue gas flows and temperatures, and steam parameters. While short-term fluctuations may reflect "natural" variations as well as temporarily unstable boiler operation conditions (including change of SRO set-points), a long range periodicity (gradually increasing temperatures over days to weeks) observed for the flue gas temperatures (boiler 1st pass (EBK), and 3rd pass temperatures) is ascribed to boiler cleaning/soot blowing events and subsequent gradually deposit build-up.
- A humidification pre-test period with water injection (covering a few hours) was also included in the data analysis, making it possible to provide a preliminary evaluation of the possible effects of humidi-

fication. This preliminary evaluation indicated an effect of humidification on certain air and flue gas parameters: -Primary air temperature after LUFO decreases (cooling effect due to the injection of water in the LUFO). -Primary and secondary air flows tend to increase (weak trend). -Gas water content after ESP increases.

The final humidification measurement campaign at Vestforbrænding, line 5, was accomplished in the week of August 10-14, 2020. Combustion air humidification was simulated by injecting water into the LUFO (humidification tests), and the influence on local flue gas temperatures was investigated by conducting suction pyrometer measurements in the furnace/boiler chamber and in the Superheater section, respectively (suction pyrometer measurements). SRO data analysis, fly ash characterization, and visual inspection of the Superheater surfaces was also part of the overall evaluation. The main conclusions from the measuring campaign were:

- During the final humidification test, which had a duration of more than 28 h, approximately 10.6 t/h of water was injected into the LUFO. The water injection test proceeded without causing any operational problems.
- Based on local humidity measurements in the primary air channel after the LUFO, it could be estimated that about 7.5 t/h of the injected water was actually evaporated and contained in the primary air stream as moisture (the steam injection contribution). This corresponds to about 70% evaporation efficiency (the remaining fraction of the injected water was removed from the bottom of the LUFO as drain water).
- An analysis of SRO data covering the final humidification measurement campaign confirmed a significantly increased water content in the flue gas after the ESP and in the stack, due to humidification. The extra moisture content amounted to a H_2O(gas) flow in the range of 11.000 – 13.000 m³/h, or about 6.6 – 7.8 t/h. This is in good agreement with the estimated value of 7.5 t/h in the primary air after the LUFO, based on the local humidity measurements.
- The SRO data analysis also revealed a slightly decreased energy efficiency of the boiler during the humidification test (going from 86.9% to 85.5% during the water injection). Since the SRO data for H_2O content in the flue gas in the stack further indicated that the condensation scrubber was not operating during this period, it was concluded that the decrease in efficiency was due to increased flue gas loss – i.e. the flue gas energy gain due to humidification had not been recovered.
- Further, the SRO data analysis revealed that an increase in the volumetric flow of secondary air during humidification test could be linked to the regulation of the O_2 content in the flue gas (as predicted by the Thermoflex modelling). In order to hold constant the O_2 concentration in the wet flue gas, the O_2 concentration in the dry flue gas is increased (by increasing the (primary) and secondary air flows).
- Considering emissions (e.g. CO and NOx emissions in the stack), the SRO data analysis did not reveal any significant differences in the emission levels with and without water injection.
- Suction pyrometer measurements of local flue gas temperatures in the furnace/boiler (1st pass) chamber and in the Superheater section, respectively, found no significant effects of humidification as compared to reference tests. According to the Thermoflex modelling, the predicted temperature decrease in the furnace/boiler chamber would be no more than maximum 40 °C (at 10 t/h steam injection) as compared to reference conditions without steam injection. The local temperatures measured with the suction pyrometer in the furnace/boiler chamber were generally in the range [800 – 950 °C] (both with and without humidification), and the short-time fluctuations were large, with temperature variations of up to 100 °C or even more within seconds to minutes. Therefore, any possible temperature effect due to humidification would be easily overruled by the "natural" fluctuations. The suction pyrometer measurements in the Superheater section showed more stable temperatures (as compared to the measurements in the furnace/boiler chamber). The short-time fluctuations (seconds to minutes) were small, but within hours to days, the temperature could vary with up to around 50 °C. Both with and without humidification, the temperatures measured with the suction pyrometer at this point were generally within the range [450 – 500 °C]. According to the Thermoflex modelling, the predicted temperature difference due to humidification at our measurement point in the Superheater section would be less than in the boiler 1st pass (only around 25-30 °C at 10 t/h steam injec-

tion), so it would be difficult to distinguish between a true temperature effect of humidification, and the "natural" variations over time.

- At the end of the final humidification test, a video recording was obtained of the Superheater surfaces by means of a camera probe. The inspection did not reveal any unusual "findings" (although it is noted that the picture quality was not very good). This is as expected, since the humidification test carried out was probably too short to verify any impacts on deposit build-up/fouling.
- Fly ash samples collected from the ash silo during the measuring campaign were characterized with respect to water content and workability (transport properties). Although the moisture content was increased slightly (from 0.26wt% to 0.76wt% with water injection) in the fly ash from humidification test as compared to the reference, the workability (flow table) test indicated that the fly ash transport properties were not deteriorated due to humidification.
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To summarize the conducted work with respect to both the modelling and the experiments conducted at Vestforbrænding, then it can be concluded that none of the observed plant operational changes when using water injection on the level of 7.5 tons per hour at a 25 ton/h (waste input) WTE plant courses concern with respect to daily plant operation. In the study was not observed any problems with respect to boiler chamber temperature, deposit formation, emission levels and ash handling properties. In case water injection is implemented on a WTE plant it would be advisable to implement a control of air supply that is based on the dry flue gas oxygen content, this to ensure that the water injection do not course an unnecessary extra supply of combustion air.

4.3 Using CAH in combustion control (WP 2, 3)

The technical advantages of CAH are:

- Fuel water content fluctuation can be counteracted by controlling the humidification (furnace, boiler and flue gas cleaning will see a more stable water content)
- Increased district heat production
- Enabling district heat production by condensation with district heat return temp. in the range 55 to 70°C
- Lower risk of corrosion due to reduced flue gas temperatures before the super heaters
- Potentially lower NOx emissions due to decreased maximum combustion temperature in combustion zone

Technical disadvantages:

- More technical complexity added to the plant
- Modifications to the combustion and boiler controls are needed in the DCS system
- Cold flue gas might need reheating to avoid droplet formation and to avoid plume visibility
- Stack need to have lining to accommodate the wet environment
- Plant layout might be challenged due to extra space need for new installations.

4.3.1 Combustion and boiler control

Currently the control of the combustion is based on keeping the actual wet oxygen level on a setpoint. When water originating from the humidification is varied due to variations in demand for production of DH it will influence the level of oxygen measured on wet basis. When more water is added it will entail that more air is added via the combustion air system to compensate for the dilution of the flue gas due to the extra water and vice versa when less water is added. This is not favorable from combustion and boiler efficiency point of view. It is best to maintain the air excess constant to obtain a stable combustion and steam production. Further extra air will also give an extra energy loss in the flue gas. To mitigate this combustion and boiler efficiency problem the control of the combustion system needs to be changed to either having a setpoint for the dry oxygen level or an air excess number.

The setpoint for the dry oxygen level or air excess number should be held constant. At some point adding extra water will dilute and cool the combustion to an extent that it will reduce the efficiency of the combustion resulting in increased CO emissions. Another parameter that could limit the addition of water is the retention time above 850 °C. Furthermore, addition of water will move the heat balance in the boiler and the addition should be limited by the temperature control of the super heaters. When the temperature control of the super heaters are getting close to their limit the addition of water needs to be adjusted to avoid too high or too low steam temperature.

Water injection in the furnace above the fuel bed in the furnace has been used for long time on WtE plants as a method to increase the fuel capacity of plants. The evaporation of the injected water and increased flue gas loss decreases the efficiency of the boiler. Consequently, it is possible to feed more fuel without exceeding the maximum steam production. This is a valuable method to increase the income for the WtE plant because the main income is the gate fee on the waste. Further water injection is also used to control the temperature level in the first part of the boiler where the SNCR system is installed. The temperature control is used to optimize the efficiency of the SNCR system by enabling injection of the reactant in the optimal temperature window. CAH is a more efficient method to obtain the temperature control and to some extent also the capacity increase.

The experience from water injection is good and no impact on fouling has been seen. Consequently, no increased fouling of the boiler is expected when CAH is installed. Unfortunately, the test carried out on Vestforbrændingen was too short to verify this.

To avoid problems with condensation and corrosion in the air preheater and the duct connection from the humidification unit to the air preheater it is needed to maintain the temperatures above the dew point.

4.3.2 Air preheater

Water jets are known to be efficient for cleaning of surfaces. Consequently, it can be expected that the installed water jets apart from humidifying the combustion air also will have a cleaning function. On the two figures below it can be seen how the water jets has affected the pressure loss and heat transfer in the air preheater.

Figure 5 Pressure loss over air preheater compared to flow and squared flow. Marked area indicates period where the test was executed.

It is not completely clear that the water jets have an impact on the pressure loss but based on the value for dP/V^2 it can be seen that the value is 8% lower after the test. This indicates that the water jets have removed enough fouling to reduce the pressure loss.

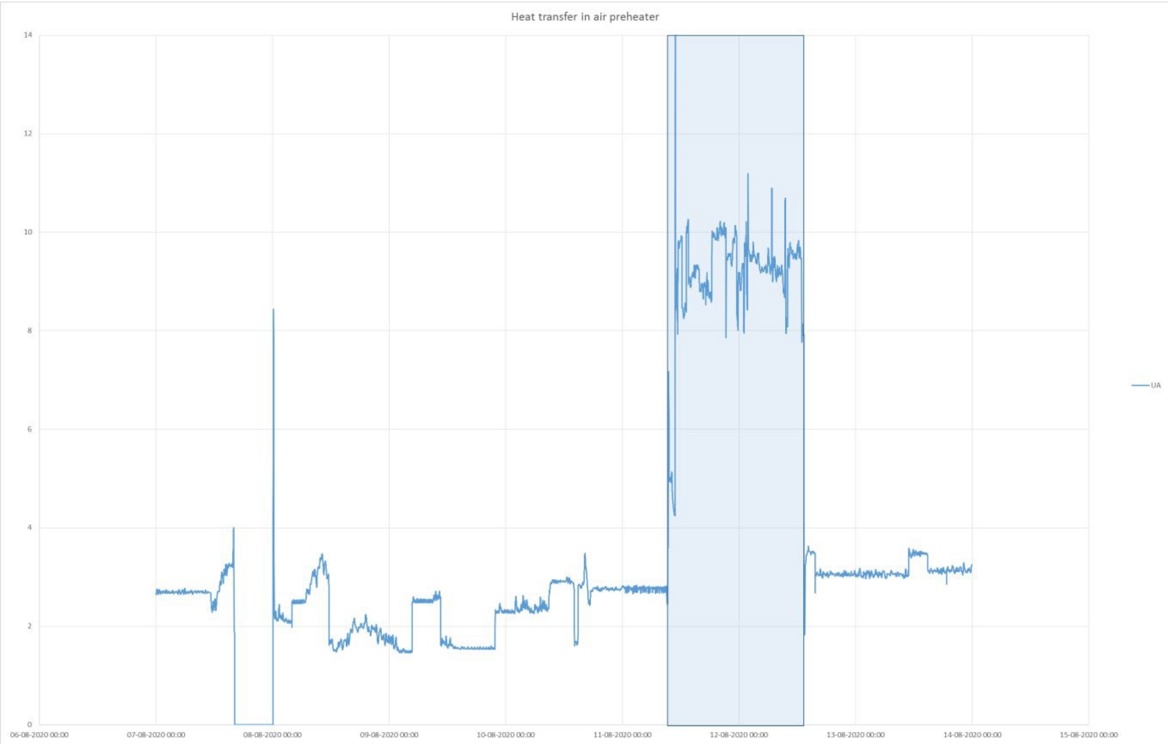

Figure 6 Overall heat transfer for the air preheater. Marked area indicates period where the test was executed.

The heat transfer in the air preheater is improved approximately 14% after the test. This indicates that the water jets have removed enough fouling to have an impact on the heat transfer even though the used nozzles are designed atomization and not for cleaning. Consequently, the humidification system in the air preheater fulfills a secondary purpose in relation to cleaning the air preheater. In a proper CAH system the water will be added in a spray tower or scrubber to support a more efficient humidification. Nevertheless, it should be investigated how the air preheater and humidifier could be integrated to obtain the same cleaning function in an integrated solution.

4.4 Retrofitting CAH (WP1, 2)

Ramboll performed a project definition brief for retrofitting full scale CAH at Vestforbrænding Waste-to-Energy facility oven-line 6. In the following section a brief summary of the main findings and conclusions are given. For the full project definition please refer to appendix 2.

4.4.1 Heating market and heat sales

The definition of the heat market and hence the potential market of the production capacity for a CAH unit are important to evaluate for the return of investment, but also to understand the operation pattern of the technology to be implemented. A load duration curve was therefore made to illustrate the expected heat consumption of the various networks (Northern and Western networks, and VEKS), for different hours of the year, and thereby determine the potential production of district heat from the CAH. When considering hydraulic limitations at heat exchanger stations (Lundebjerg and Bagsværd), it is estimated that the total CAH-production to VF consumers in 2025 will be 33.9 GWh.

To see how the CAH would perform at various operational conditions, it was further investigated how different district heat return flows and temperatures influence the heat capacity by the CAH, and it was found that it is possible to produce a certain district heating capacity (MJ/s) within a range of volume flows and return temperatures. This was followed by measurements of the actual volume flow and return temperatures at different locations in the network, to see how these parameters change throughout the year, when the district heat demand changes. It was used to estimate the CAH district heat capacity to the given network in the given time of the year.

The results are presented in Tabel 1. In the blue rows in the table, return temperature and volume flow at the given network and corresponding CAH capacity is shown. In the green rows of the table the resulting return temperature to the absorption heat pump (AHP) for the various CAH connection modes are shown. The increased return temperature will result in a reduction of the heat production from the AHP as indicated in the table. But this will also reduce the steam supply to the AHP which will be converted to electrical and thermal power. However, all in all the reduced AHP heat production will to a certain degree decrease the benefit from the CAH. The values are given for three periods of the year:

2014-09-14, 00:00 to 2014-09-30, 23:00 (summer Part 1)
2014-10-01, 00:00 to 2015-03-31, 23:00 (winter)
2015-04-01, 00:00 to 2015-09-14, 23:00 (summer Part 2)

It is seen that during the winter a benefit of approx. 9.9 MJ/s to 13.5 MJ/s from CAH can be obtained based on the return water from northern network with the low return temperature. During the summer the heat capacity is reduced due to the reduced flow.

If the total flow from the northern network, western network and VEKS are utilized a benefit of approx. 9.3 MJ/s to 13.3 MJ/s can be obtained. During the summer the heat capacity is reduced due to the increased return temperature to the AHP. Compared to the situation based on the return flow from the North network, the larger volume flow will in this case compensate for the higher return temperature.

Furthermore it is seen that the lower return temperature obtained by removing the Lundebjerg heat exchanger station will only have an minor effect on the benefit from the CAH as the capacity will be increased by 0.5 – 1.0 MJ/s.

It is therefore concluded that the mixed return water from the northern network, western network and VEKS will be suitable for the CAH and the removing of the Lundebjerg heat exchanger will have only minor influence of the CAH benefit.

4.4.2 Technical basis

Based on the flue gas flow and water content during Q1 2015, the potential energy release from direct flue gas condensation have been estimated. It was assumed that the flue gas could be cooled to 60 °C in the condenser, with a district heat return temperature of 57 °C. As shown in Figure 3, the potential is stable around 4 MJ/s, consistent with the stable moisture content.

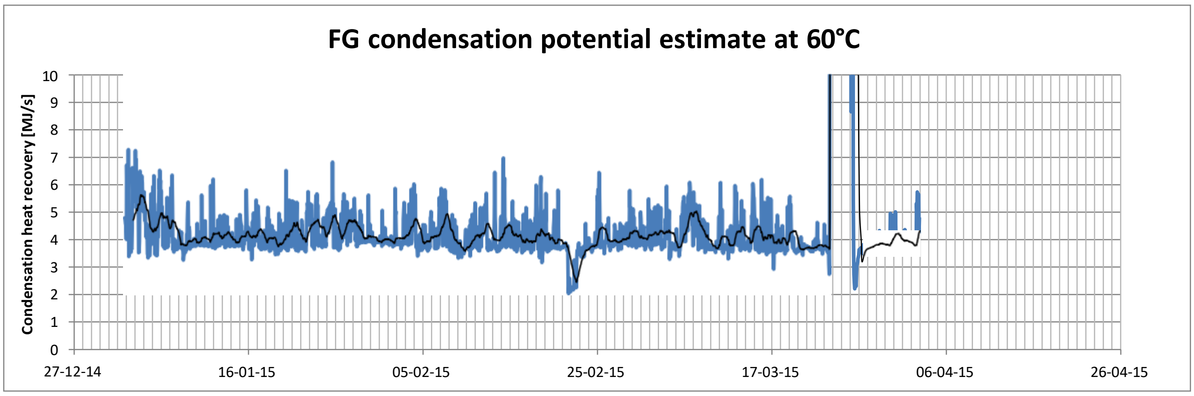

Figure 1 Estimated heat potential from direct flue gas condensation on VF6 during Q1 2015 if flue gas was cooled to 60 °C, which is possible with a district heating return temperature of 57 °C.

The red line in Figure 4 shows how the heat potential from flue gas condensation will be significantly increased, if the flue gas can be cooled to lower temperatures. This can e.g. be achieved using heat pumps as currently implemented on VF5. Another option is to humidify the combustion air from moisture recovered downstream the flue gas condenser. The estimated potential heat using this method is indicated by the dashed purple line.

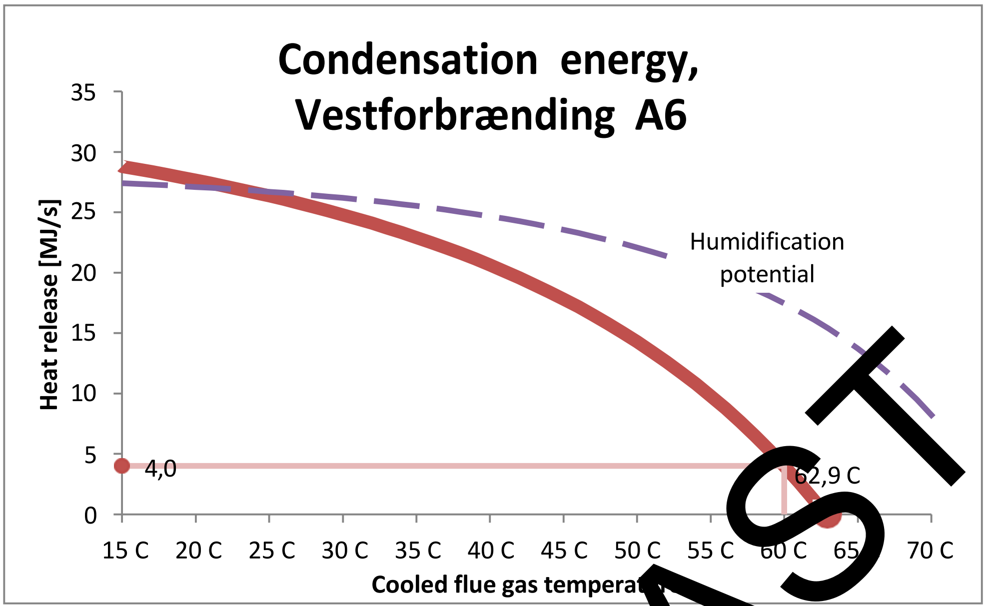

Figure 2 Heat recovery potential from flue gas condensation at different cooled flue gas temperatures.

If the condenser can cool the flue gas to 60°C, the humidification system may extract up to approximately 17 MW, which is around 13 MW more than the 4 MW available using direct condensation.

The model of the system was later refined, and further parameters were taken into account (an air leakage was discovered and fixed in 2016 and a planned 3rd flue gas treatment was implemented in the model) which slightly reduced the CAH potential compared to Figure 4. The expected heat production with CAH with 57°C district heat return temperature is then 15.1 MJ/s, which is 10 MJ/s more than would be possible with simple direct condensation system.

The change in CAH heat production to the parameters; district heat return temperature, humidifier performance, and waste heating value was determined. The sensitivity is shown in Figure 5, Figure 6, and Figure 7. The red dot indicates the modelled operational point.

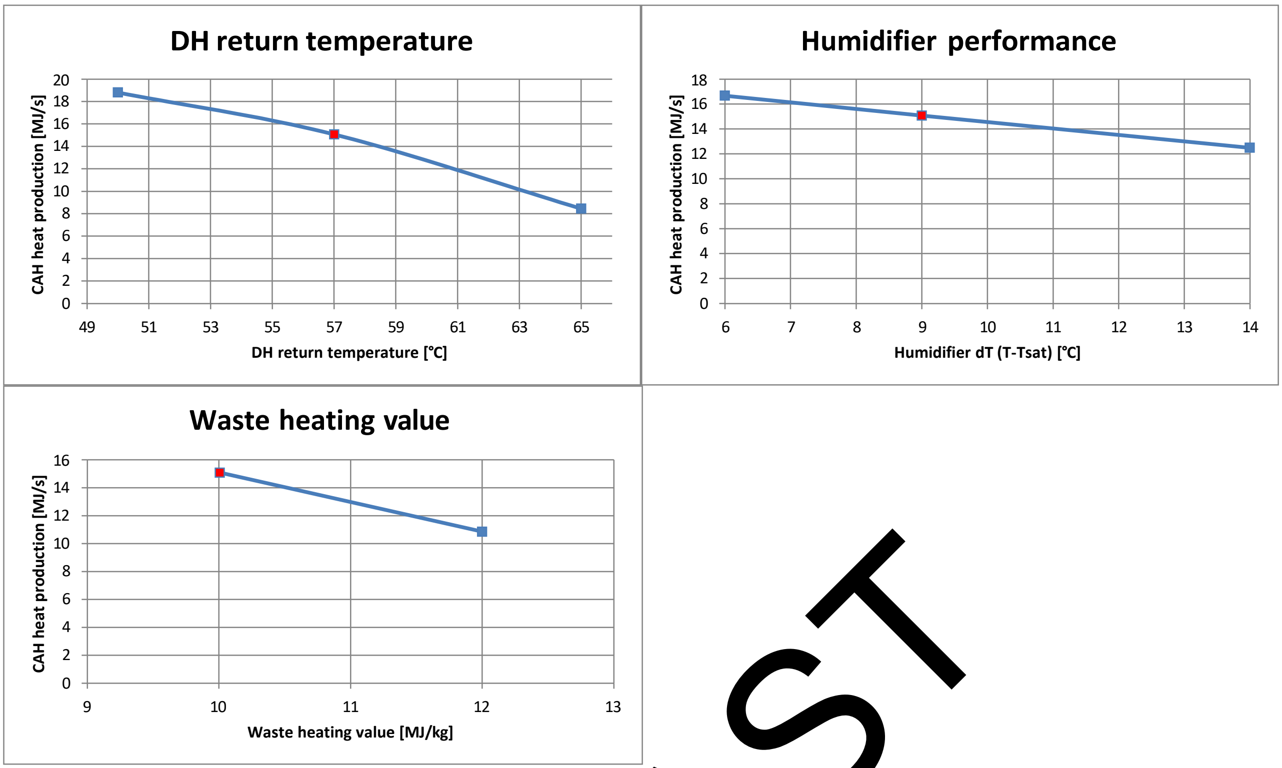

Figure 3 Sensitivity of CAH heat production towards DH return temperature. Of CAH heat production towards humidifier performance (difference between incoming water temperature and saturation temperature of outgoing air. And of CAH heat production towards waste heating value.

4.4.3 Technology selection

The basic system consists of a condensing unit for direct condensation with exchange of heat between the flue gas from the existing flue gas treatment system and the district heating water (return).

The flue gas will have a further potential of heat recovery by condensing, after the direct condenser. To recover this potential, it is the intention to use the inlet combustion air as a cooling source, by transferring the recovered condensation energy from a final condensation step to the combustion air stream and use it for evaporation of water. This is done by adding a second condensing step in the flue gas path, cooled by a water flow, circulating between the final condenser and a humidifier unit installed in the combustion air duct.

As a result of the increased content of water vapour in the combustion air, the flue gas will have an increased content of water after the boiler of about 10 %(vol), and subsequently the heat recovery potential of the direct condensing unit will be higher with the humidification unit than without.

An evaluation of all equipment necessary for the flue gas condensation and humidification was made. Below is a list with the main conclusions found for each component which needs to be updated/ installed in order to facilitate the design.

- Equipment for direct flue gas condensation: Could be designed as a condensing scrubber or a direct heat exchanger:
  - The condensing scrubber is designed as a packed bed scrubber column, wth either structured or dumped bulk packing. Above the packed bed, a water distribution system should be located.

- The direct heat exchanger is a tube heat exchanger, with flue gas passing through inside the tubes and district heat water on the outside of the tubes.

Both condensing units should be made of corrosion resistant material such as 254 SM or Titanium, due to potentially small amounts of chloride in the flue gas. A frequency-controlled pump for either bypassing the condensing unit or to let the district heat stream flow through the condenser, should be installed.

- Equipment for final flue gas condensation: Requires same equipment as for the direct flue gas condensation. At the outlet an efficient demister should be installed, to separate droplets from the gas, before the induced draught (ID) fan.

- Selection of condensing unit type: The heat exchanger has a higher potential for heat recovery rate, but it is however more difficult the detect possible corrosion damages. This would be easier with a scrubber combined with an external plate heat exchanger. Additionally there is a higher pressure drop in the heat exchanger for the flue gas side compared to the scrubber.

- Equipment for humidification: The humidification unit could be a packed bed scrubber and should be divided in two units. When considering the bed heights, a scrubber sump, space for air inlet duct, water distribution arrangement, a demister unit, a possible redistribution unit, and space for maintenance, the total tower height is estimated to 20 m to 24 m. The diameter of the humidifier unit is estimated to 6 m.

  The combustion air is usually withdrawn from the waste bunker, which would result in the water circulating through the humidifier being polluted with dust and microorganisms of primarily organic types. A bleed stream should therefore be removed to avoid suspension of particles in the water loop. The water should be filtrated and discharged to the sewer or fed to the furnace or waste hopper. Make-up water should be applied to the circulating loop to ensure the flow throughout. This could be condensate from the condensing system.

- Intermediate heat exchanger: It is recommended to install an intermediate heat exchanger between the humidifier and the condensing unit to use two separate water loops for these units (and thereby minimize the risk of clogged packing in the scrubber and fouling and corrosion in the heat exchanger). This could be a plate heat exchanger, as it is easy to disassemble and clean.

- ID fan: Due to increased flue gas flow rates the pressure drop on the suction side of the ID fans will increase, thereby increasing fan power. It is therefore necessary to either replace the existing fans or use the existing ID fans of line 1 and 2.

- Combustion air system: It is necessary to install a booster fan to handle the flow and pressure loss through the humidifier, preheater and air duct system. The fan should be placed before the humidifier.

  New combustion air intakes should be made in the existing bunker at a location, that minimizes the dust. Additionally, a possibility for air intake from the boiler hall should be made.

  The combustion air ducts should be corrosion protected or replaced by a system with corrosion resistant material. The ducts must be insulated.

- Flue gas reheating and emission measurement system (EMS): With the current stack design, it would be required to install a reheater, to avoid corrosion in the duct. As an alternative, the duct material could be replaced or recoated. If flue gas reheating is not installed, it should be ensured that the EMS can still operate properly at the new conditions.

The proposed process flow diagram after implementation of combustion air humidification is shown in Figure 8.

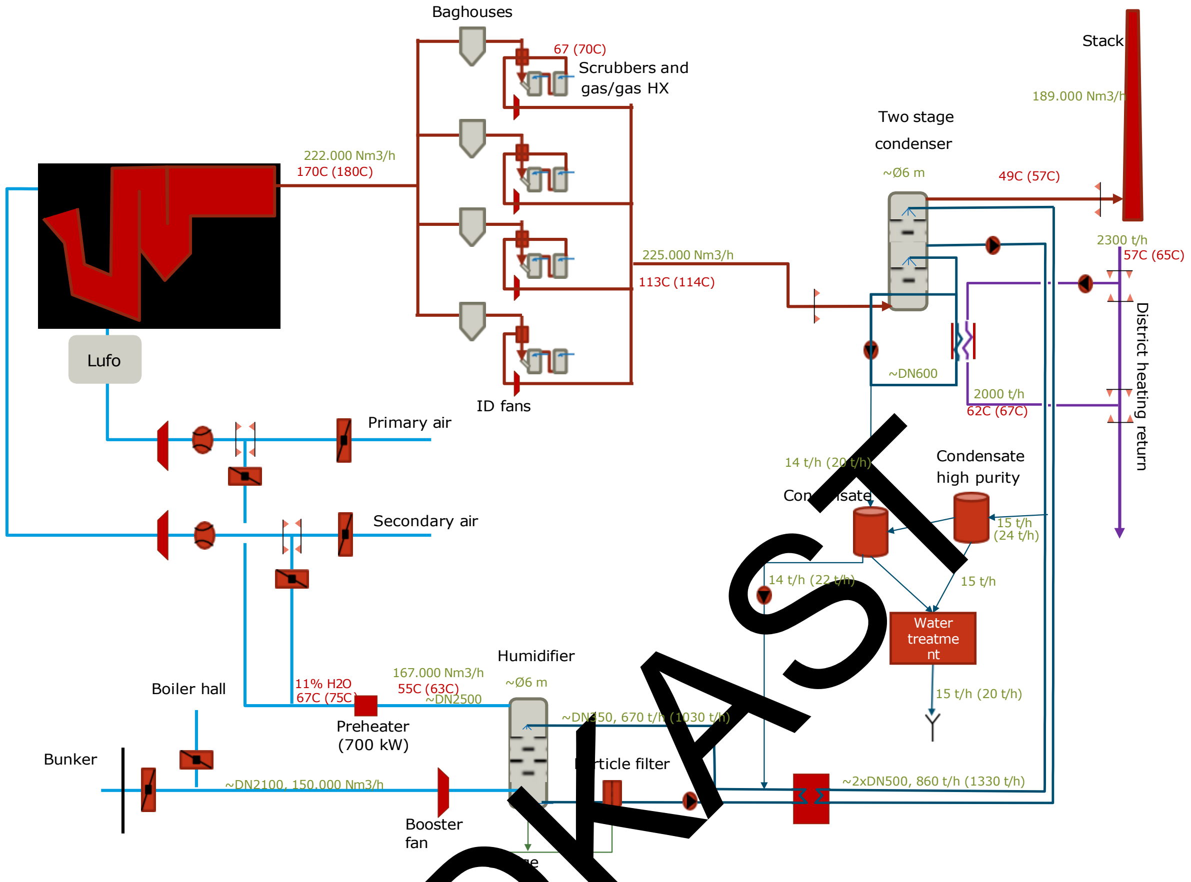

Figure 4 Sketch of the VF6 process after implementation of combustion air humidification.

4.4.4 Financial assessment

A financial assessment of the use of CAH, including the possibility of heat sales, actual heat market etc was made. It includes evaluation of CAPEX and OPEX. The assumptions used for the assessment can be found in appendix 2 chapter 6.

The operation of CAH will generate increased cost on 11 MDKK and increased heat sales on 29 MDKK resulting in a change net income on 18 MDKK per year. With an investment on 90 MDKK it is clear that the pay-back time is short.

In Figure 9 the pay-back time is illustrated graphically with the cash flow of the project. The calculated pay-back time is 5.4 years and the calculated net present value of investment and cash flows over 10 years is 68 MDKK.

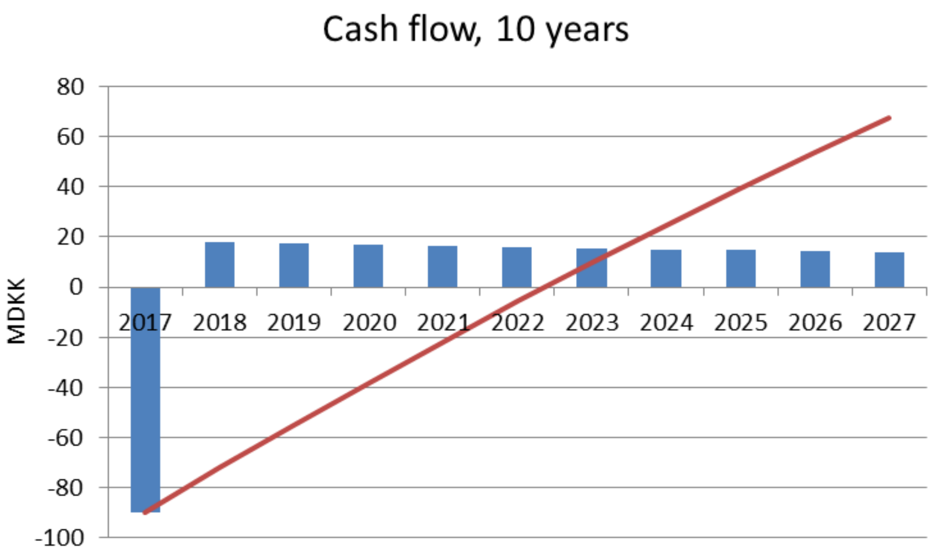

Figure 5 Graphically illustration of cash flow and pay-back of CAH project in basic calculation.

4.4.5 Permitting and EIA

The following permits should be gathered before conducting the project:

- A VVM-screening is most likely required to prove that the project decreases or only slightly increases the environmental impacts.
- Authorization for increased amount of waste water emissions.
- A planning permit should be retrieved from the municipality.
- A new environmental approval is required.

4.5 Field scale and full scale (WP5)

When compared to full scale the field scale demonstrated a relatively large water evaporation and fulfilled the expectations of representing full scale to a large extend. Therefore, most conclusions can also be used as a relevant indication as to how full scale will work. The experiments conducted with the field scale CAH equipment evaporated 7,5 ton/h in average with large variations as expected also in the field scale. Full scale installations expect to evaporate between 14 and 22 ton/h and hence the field scale obtained more than 50% of full scale expectations.

Table 1 Comparison of capacity of field scale and full scale. * immediately after the CAH unit

	Unit	Full scale (norm.)	Full scale (max)	Field scale test
Water evaporation	ton/h	14	22	7,5
Heat of evaporation	MW	9,3	14,7	5,0
Dewpoint of combustion air*	°C	55	63	56

The full scale facility represented by Vestforbrænding line 6 is calculated to produce between 15 and 18 MW of additional district heating via direct condensation when the CAH unit is installed and the flue gas is cooled to between 49 and 57C primarily affected by the district heat return temperature. The conducted experiments conclude that this is possible without influence on the daily operation, energy production, emissions control or waste treatment capacity. Furthermore, experiments concluded that fly ash will not change properties when operating CAH

4.6 Projects and relevance (Ramboll)

This project set out to investigate and conclude the optimal design of a full scale CAH unit installed at the waste to energy facility Vestforbrænding line 6 and investigate concerns of several issues affecting the operation of the facility and its performance. As the full scale testing and optimization was not possible the project was changed to test CAH at field scale and focus of evaluating its relevance as well as investigate key concerns. The construction of the field scale CAH unit and the operation and measurements during tests were overwhelmingly successful. CAH was proven to be a viable and reliable technology and the concerns were proven to not be negatively influencing operation nor performance.

The project have provided the confidence in the technology to work towards commercialisation and marketing as a real alternative to heat pumps or to save steam or power consumption for heat pump operation. The Waste-to-Energy market will, based on the results of this project, see this technology deployed in the short future. This is especially true if Carbon Capture and Storage (CCS) is to be implemented on these facilities which seems more likely now than ever. CCS requires constant and year round cooling of the flue gasses and hence will require much more heat pump work to ensure cold flue gasses (also when no heat sales is possible). In such scenarios CAH provides a cheap and effective mean of cooling the flue gas loosing as little power sales as possible. Furthermore, CAH will prove very effective if or when Power-to-X makes O_2 available as a biproduct from H_2 production.

The project has been presented at industry conferences (SAF 2018) and at industry group meetings (DAFONET 2017). DTU is investigating how to publicize results. B&W Vølund will be using results in marketing material and as sales arguments.

Utilisation of project results

The current project is a prerequisite for the CAH investments with Danish as well as Northern European Waste to energy facilities. Without the current project the uncertainties related to the implementing CAH and the subsequent investment would be too large. The EUDP funds allowed for test and research of CAH to initiate market penetration and open the commercial potentials with the knowledge and experience gained in the project. Partners now have a head start in the market. The EUDP support was instrumental, from an economic point of view, as a mean for bringing the partnership together and for ensuring adequate dissemination of the results.

Energy policy

The potential improved efficiency based on CAH is significant and it provides the flue gas conditions needed for Carbon Capture and is part of the preparation for Power-to-X both important Climate as well as energy policy strategic goals.

Based on the conclusions of this study facility owners will be able to take advantage of the ability to control power and heat production independently assisted by CAH. This makes it possible to run heat only production (without co-production of electricity) when other, greener energy sources, such as wind turbines, produce enough power to cover the demand. And when wind turbines overproduce electricity, this technology can convert electricity very efficiently into heat utilizing the full potential of large efficient heat pumps. These changes can, when implemented, potentially lead to a very significant reduction of fossil CO2 emissions in Denmark for years to come and in the fossil free future provide efficient conversion and storage of electric energy as well as efficient and cheap district heating.

Rambøll, B&WV

The research and test results provide invaluable knowledge about CAH for WtE, giving significant technical advantage towards international clients and sales of new services. Without the support from EUDP there would not be resources to get the extensive test and research result, that can be used to model the performance of the CAH facilities on other WtE facilities.

DTU

This project has sparked the first collaboration between DTU CHEM and Rambøll. We expect that the collaboration will lead to collaborative student projects and further research projects. The research to be performed in the project is highly relevant for DTU CHEM, is state-of-the-art and has no known prevalence. Without the support from EUDP, DTU could not participate in the project.

Vestforbrænding, AffaldPlus and AffaldVarmeAarhus

The support from EUDP freed resources from the facilities to follow the results and bring knowledge into the project about differences in operation facilities in-between. This will provide invaluable information to evaluate a similar investment in CAH.

Project conclusion and perspective

The project has provided the required confidence in the Combustion Air Humidification (CAH) technology to work towards commercialization and marketing as a real alternative to heat pumps or to save steam or power consumption for heat pump operation. The project partners have gained first-hand experience with the technology and confidence in the technology in terms of its operational stability. Furthermore, any concerns with regards to negative effects on plant performance and availability have been proven not be true and positive effects on existing problems with regards to keeping air preheaters clean have been noted as an advantage of this technology.

The Waste-to-Energy market will, based on the results of this project, probably see this technology proposed and probably deployed. This is especially true if Carbon Capture and Storage (CCS) is to be implemented on Waste-to-Energy facilities which seems more likely now than ever. CCS requires constant and year-round cooling of the flue gasses and hence will require much more heat pump work to ensure cold flue gasses (also when no heat sales is possible). In such scenarios CAH provides a cheap and effective mean of cooling the flue gas loosing as little power sales as possible. Furthermore, CAH will prove very effective if or when Power-to-X makes O_2 available as a biproduct from H_2 production.

Studying implementation in full scale of CAH together with new technologies such as large plant heat pumps, Carbon Capture, Power-to-X, large sea-cooled heat pumps or large seasonal heat storages would add additional knowledge of and development of the CAH technology and would make its implementation more viable to the energy producers and waste-to-energy facilities.

5. Appendices

1. DTU report 1: Plan for measurements of baselines
2. Ramboll Report 1: Project definition CAH on Vestforbrænding line 6
3. B&W Vølund Technical Note 1: CAH Performance
4. DTU Report 2: Humidification Final Rporting