ENHANCED FLUE GAS CONDENSATION TECHNOLOGY: ANALYSIS OF A 10MW DEMONSTRATION PLANT

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A study on the application of an active condensation system to a typical Austrian heating plant fed with wood chips is presented. The heating plant consists of two biomass boilers (5MW+3MW). The flue gas of both boilers is mixed and directed to a condensing heat exchanger for heat recovery. The heat gained in the heat recovery system is used for preheating the reflux. A heat pump was integrated to enhance the heat recovery. In this paper the integration of the heat pump is discussed. All parts are modeled to calculate the potential energy gain which is obtained and to assess the usefulness of the application of a heat pump from a thermodynamic point of view. In addition, an economic analysis was carried out to evaluate the payback time for the heat pump using the typical Austrian heat and electricity prices. Finally first measurement results are discussed.
Keywords: district heating, combustion, demonstration, efficiency, economics, heat pump

1 INTRODUCTION

Biomass has a long tradition as renewable energy source for heating purposes. Biomass based heating systems can be found in a wide load range from small stoves with 5kW nominal load to heating plants with MW heat load feeding district heating networks. Today highly developed technologies with high energy efficiencies are available in all sizes.

However, there is still potential to enhance the energy efficiency of most systems. Woody biomass has a high water content ranging from 10% in industrial pellets up to 50% in fresh woodchips. Furthermore it contains about 6% hydrogen based on the dry fuel mass. Both the water and the hydrogen lead to a high water content in the flue gas, which can be seen in the big difference between higher and lower heating values. This energy, stored as latent heat in the water vapor, is only available at low temperatures, below the dew point of the flue gas. In typical heating applications the latent heat cannot be regained, because the return water temperature is too high.

One option to improve the energy efficiency of the system is the application of a heat pump to overcome the drawback of the low temperature. This concept is called “Active Condensation”. Different heat pump concepts like thermal or compression type heat pumps can be applied. The advantages of compression heat pumps to thermal heat pumps are the lower investment costs as well as the wider range of applications already on the market. The drawback is the additional electricity input. Thus a detailed evaluation of the concept is necessary to determine useful application areas.

During this study the application of a compression heat pump is discussed as a possibility to regain the latent heat in the flue gas. The heat pump uses the flue gas as heat source at low temperatures and returns the heat at the temperature level of the return flow. Based on the data of one typical heating plant in Austria, the implementation of the heat pump is discussed. Both the heat exchangers for heat recovery and the heat pump are modeled, to evaluate the possible efficiency increase. Furthermore the economic viability is discussed. Finally the first measurement results of the demonstration plants are presented and compared to the base case without active condensation.

In particular district heating networks are often provided with biomass. Therefore the results of this demonstration have a wide impact for further use in Austria. A total amount of 1.000 installed heating plants, each one having a nominal heat output exceeding 1 MW [1], are installed in Austria. In total, these heating plants sum up to a heat output of 2.800 MW.

2 DESCRIPTION OF THE HEATING PLANT

First a short description of the heating plant is given. Afterwards the integration of the heat pump is discussed and the monitoring introduced.

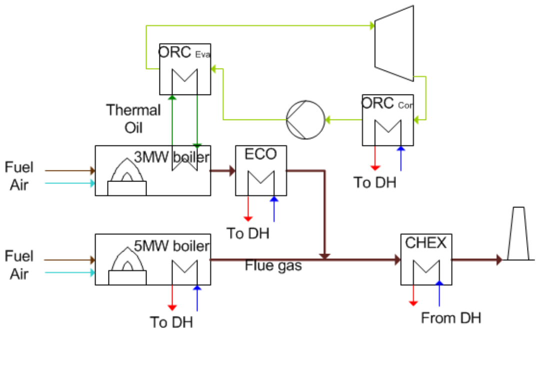

Figure 1: Sketch of the plant. DH – district heating, ORC – Organic Rankine Cycle, CHEX – condensing heat exchanger, ECO - economizer

2.1 Plant description

Figure 1 shows a sketch of the heating plant. The heating plant was originally installed with two furnaces (5 + 3 MWth nominal load). The 5MWth furnace is operating as water boiler, thus the heat is directly fed to the district heating. The second furnace (3MW boiler) is operated with thermal oil driving an organic rankine cycle (ORC) with a nominal electric load of 0.52 MWel. The ORC cycle condenser and the economizer (ECO) release the heat to the district heating, leading to a high total first law efficiency (heat and electricity). The flue gas of both boilers is mixed and directed to a condensing heat exchanger (CHEX) designed for 2.3MW. The heat gained in the condensing heat exchanger is used for preheating the reflux. Figure 2 shows the hydraulics of the heating plant.

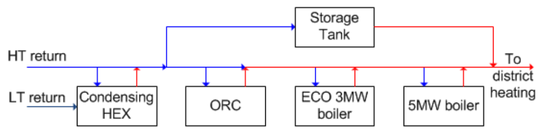

Figure 2: Sketch of the plant hydraulics. ORC – Organic Rankine Cycle, ECO - economizer

Table I shows the average value of the heat load of the district heating as well as the heat and electricity produced in the two furnaces and the heat recovery device during the heating season (165 days based on 2011/12). As can be seen in the table, the return temperature is 54°C, which is approx. the dew point temperature. Thus, with the actual design hardly any condensation takes place in the heat recovery. Still the heat recovery system is designed as condenser, so it would be possible to operate it in condensing mode. The total heat input in form of the net calorific value was estimated with the typical fuel composition of wood chips with a high water content (45.0%H_2O, 27.5%C, 3.3%H, 24.2%O). The ORC cycle is operated during the whole year, while the 5MW furnace is only used during the heating season and adapted to the actual heat demand.

Table I: District Heating with HT (high temperature) and LT (low temperature) return

District Heating	Value
Supply temperature	95°C
HT return temperature	54°C
LT return temperature	39°C
LT/HT heat load	21/79

Table II: Input data for model

Plant	Value
Fuel water content	0.45kg/$kg_{w.b.}$
Air ratio	2
Flue gas temperature at CHEX inlet	175°C

2.2 Integration of the heat pump

As described in the introduction, the integration of a heat pump into the heating plant will be evaluated. The heat pump should increase the heat gain in the condensing heat exchanger (CHEX). Figure 2 shows the condensing heat exchanger before the heat pump integration while Figure 3 shows the integration of the heat pump into the heating plant. The condensing heat exchanger is a tube bundle heat exchanger containing 5 tube bundles. These tube bundles are splitted in three heat exchangers (HEX1, HEX2, HEX3). The three heat exchangers work on different temperature levels. HEX1 has the lowest incoming temperature. It is connected to the heat pump evaporator (HP_{EVA}). HEX2 has a slightly lower temperature level than the reflux from the district heating. HEX3 is fed with the heated water coming from the heat pump. In most cases it will work in non-condensing mode.

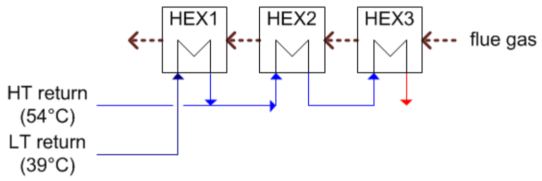

Figure 3: Sketch of the condensation system before the integration of the heat pump.

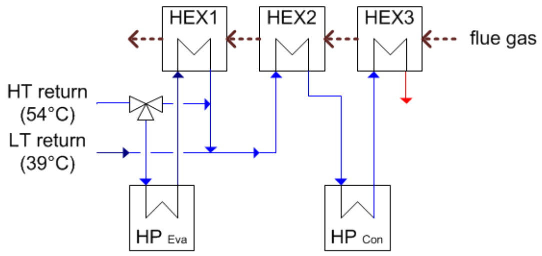

Figure 4: Sketch of the active condensation system: Condensing heat exchanger with heat pump.

2.3 Measurement setup & data evaluation

To monitor the plant all heat producers (both boilers, ECO, heat pump, condensing HEX) are equipped with heat meters, giving the volume flow, temperatures and energy in a 10 seconds interval. Additionally the condensing heat exchanger temperatures on the water and gas side are measured before and after each tube bundle, making it possible to calculate the heat load of the bundles separately.

The electricity of the overall plant as well as the electricity need of the heat pump is monitored in 15 minutes interval. Hourly averages of all measurement points were calculated.

3 MODEL

The total system containing the two furnaces, the flue gas heat recovery and the heat pump were modeled, to evaluate the impact of the heat pump installation. Because the good estimation of the heat transfer in the heat recovery of the flue gas is crucial for the analysis, effort was put into a good estimation using physical and empirical equations. In the last step the heat pump is described with manufacturer data.

The system is modeled in Matlab/Simulink. All parts are connected via flue gas and water connections as in figure 1 to 3. For a given heat demand the steady state operating point is searched by changing the heat load of the 5MW boiler until the designated heat load is equal to the heat load of all components. The results are compared to the model without active condensation.

3.1 Boilers

The boilers were modeled according to the data in table I-II. The 3MW boiler is operated at steady state, while the load of 5MW boiler is changed according to the heat demand. The losses of both boilers were estimated according to measurement data from the heat meters, the fuel input and the flue gas outlet temperature.

3.2 Condensing heat exchanger

A model is set up which considers both convective heat exchange as well as heat due to condensation. For each tube the gas side and water side heat transfer coefficient is calculated. On the gas side the Nusselt number is calculated with the equations for a tube bundle heat exchangers [2]. On the water side the equations for flow inside of a tube with constant wall temperature are used.

The mass transfer coefficient for the water vapour is derived after the concept described by [3]. It scales with the gas side heat transfer coefficient and the logarithmic mean of the mol fraction of the inert gas between bulk and wall.

In the model the low temperature return flow was neglected because of the lack of data. The monitoring was set up after the heat pump installation, and therefore the flow rate was not known during the economic evaluation before the integration. Therefore for the base case it was assumed that all return flow has the same temperature and flows through HEX1-HEX3.

3.3 Heat pump

The heat pump is described using manufacturer data. R236fa is used as a refrigerant, because it is particularly suited for relatively high temperature applications. For modeling the source temperature is always set to 40°C at the outlet, while the sink temperature can vary. The coefficient of performance (COP) of the heat pump is adapted depending on the sink temperature with a spline interpolation as can be seen in Figure 5 based on measurement data.

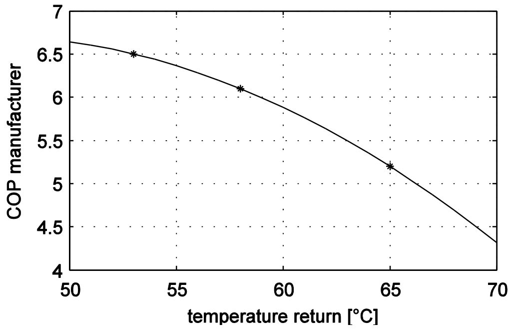

Figure 5: Coefficient of performance of the heat pump depending on the inlet temperature of the sink.

The heat pump is constructed with four refrigerant circuits and eight compressors. This leads to a good performance independent of the load. Thus the COP is not changed for different heat loads but it does depend on the inlet temperature of the heat sink.

4 RESULTS

4.1 Model results & economics

Based on the average plant operation (6.12MW heat output) the model results with and without heat pump were calculated. The base case without heat pump reaches 914 kW in the condensing heat exchanger. The active condensation case (after the integration of the heat pump) shows a heat load of 1421kW in the condensing heat exchanger. At the same time the fuel input to the plant can be reduced by approximately 10% (7.15MW compared to 7.93MW based on the NCV) but with an addition of 127kW of electricity. The COP of the heat pump equals 6.2. Further results are presented in Table III.

Table III: Model results before and after the heat pump integration

	Before	After
Power boilers	5.20MW	4.57MW
Power HEX3	914kW	1421kW
Electric Input Heat pump	0kW	127kW

An economic analysis was carried out with fuel costs of 18EUR/MWh (NCV based) and electricity costs of 10c/kWh. In the analysis the storage losses and heat losses of the biomass are accounted for. Furthermore the electricity of the plant as well as for the heat pump is calculated. The economic evaluation shows a decrease in operating costs of 40.000EUR/a between active condensation and base case.

The payback time was calculated for an estimated installation cost of 300.000EUR. The fuel and electricity interest rates are varied between 3 and 6%. This leads to operating cost reduction between 37.000EUR/y and 91.000EUR/y during the next 12 years, resulting in a payback time between 6 and 8 years.

4.2 Measurement results

The heat pump was installed in December 2012. First measurement results from 16th of February 2013 until 31st of March were evaluated and compared to the same time slot in 2012. Figure 6 gives the average power per bundle in the condensing heat exchanger before and after the heat pump installation. Because of lack of data, in 2012 only the bundles in HEX2 and HEX3 are monitored together as ‘old’. In 2013 a detailed monitoring of each heat exchanger part was possible. The comparison shows that the power in HEX2 and HEX3 increased significantly in 2013 compared to the old setup. Further on the power output of HEX1 shows the high possible heat transfer in flue gas condensing mode.

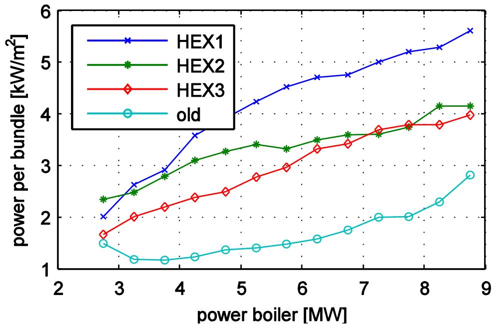

Figure 6: Heat transfer in the condensing heat exchanger before and after the installation.

By estimating the heat load in HEX1 during 2012, an evaluation of the total heat load between 2012 and 2013 is possible. Figure 7 shows the total heat load divided by the boiler power (ORC + ECO 3MW boiler + 5MW boiler), giving the excess heat compared to the boiler only operation. In average the ratio increased from 1.16 in 2012 to 1.31 in 2013. Figure 7 shows that the increase is larger for lower boiler powers. While in 2012 the ratio decreases with lower boiler power, in 2013 the ratio slightly increases with lower boiler power.

However, the variations are high which indicates the short measurement time as well as high fluctuations in the operation of the plant. Further influences e.g. from varying fuel water content and fluctuations in the air ratio need to be analyzed to fully understand the heat transfer in all operating conditions.

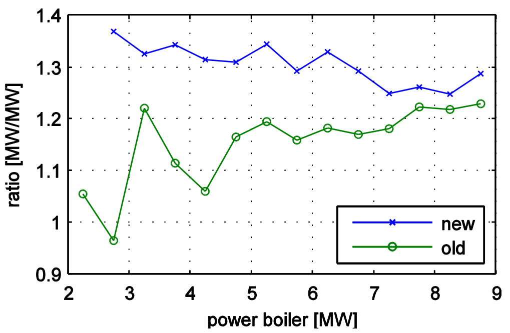

Figure 7: Total heat output compared to boiler power

Furthermore, the electricity demand of both time slots was compared. In 2012 the electricity demand of the plant was 29,0kWh/MWh. After the heat pump installation the electricity demand was 50,6kWh/MWh from which 28,1kWh/MWh account for the plant operation and 22,5kWh/MWh for the heat pump operation.

5 CONCLUSIONS AND OUTLOOK

During this study, the integration of a heat pump into the heat recovery system of a 10MW heating plant was evaluated. The heat pump lowers the temperature of parts of the reflux. In consequence, the heat recovery can work partially in condensing mode. This leads to a higher heat transfer rate and by this to an enhancement of the recovered heat. After the condensation, the heat pump sink is integrated, returning the before subtracted heat of the reflux.

This active condensation system was evaluated on the basis of an existing heating plant in Austria. The tube bundle heat exchanger of the heat recovery system was modeled with literature heat transfer correlations. The heat pump was modeled based on performance data of a heat pump manufacturer.

Applying the model, the electricity and fuel input of the actual heating plant for the average heat demand was compared to the energy input after the integration of the heat pump. The results show, that the fuel input can be reduced by 10 %. At the same time the electric input to the heat pump is 127kW.

Based on the thermodynamic evaluation the economic viability was evaluated using the net present value method. The results lead to an operating cost reduction of 40.000 € per year, causing a payback time of 6 to 8 years. The analysis of the economic situation shows a strong dependence on the heat pump operation and energy price trends. Hence, the accurate control of the heat pump is of great importance for the beneficial operation.

The heat pump was installed and a monitoring was set up. First measurement results show a strong increase in the bundle heat load (see figure 6). The share of power output from the condensation compared to boiler only operation increased from 16% to 31%. However, further evaluations are necessary to integrate the changing fuel characteristics and air ratio.

In the future the model will be validated against measurement data. Based on the adapted model the performance of the whole plant will be optimized according to varying fuel and electricity costs leading to a control strategy for the plant operators.

In conclusion, the integration of an active condensation device into a heating plant can be operated beneficially. Thus active condensation is a measure for efficiency increase both in energetic and economic point of view. However, because of the sensitivity of the economic viability to the electricity and biomass prices, supporting reasons for the integration are highly welcome.

6 REFERENCES

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