**Motivation**

State of the art boilers reach high efficiencies based on the lower heating value (LHV), but still show high losses compared to the higher heating value (HHV). Typical efficiency (HHV):

- Pellets: 85% to 89%
- Wood chips: 73% to 81%

Accordingly, an “active condensation” (AC) device being able to transfer the latent heat to the return flow strongly enhances the efficiency.

**Concept & Model**

The AC was modeled with mass and energy balances:

- Quench: Cool down flue gas and condensate water vapor (AC - Condensation)
- Heat pump: Transform low temperature heat from quench water to reflux temperature (AC - Active part = electricity input)
- Input parameters: Fuel & air: 25°C; Air: 0% humidity; Fluegas after boiler: 120°C; Excess air ratio: 1.5

**Results**

By means of modelling, and mass and energy balances the increase of energy efficiency was estimated (Figure 3).

![Fig 3: Boiler efficiency with active condensation for different quench outlet temperatures. Red: 35°C; green 25°C; blue: 10°C; black: without AC. (a) for different fuel water content (b) for different return temperatures.](image)

The economic situation was evaluated according to actual biomass and electricity prices.

![Fig 4: Operation costs for different quench outlet temperatures. Red: 35°C; green 25°C; blue: 10°C; black: without AC. (a) for different fuel water content and medium applications (wood chips 3c/kWh, electricity 10c/kWh) (b) for different return temperatures for small applications (pellets 6c/kWh, electricity 19c/kWh).](image)

**Conclusions**

- Active Condensation increases the energy efficiency in all calculated cases. Higher water content leads to higher efficiency increases.
- For high quench outlet temperatures and high return flow temperatures the operation costs decrease. The operation costs strongly depend on fuel and electricity prices.

**Literature**


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Thermodynamic and economic analysis of an active flue gas condensation device for domestic biomass boilers

Babette Hebenstreit(1,2), tel.: +43 7416 52238 43, email: babette.hebenstreit@bioenergy2020.eu
Rosemarie Schnetzinger(1), tel.: +43 7416 52238 72, email: rosemarie.schnetzinger@bioenergy2020.eu
Ernst Höftberger(1), tel.: +43 7416 52238 22, email: ernst.hoeftberger@bioenergy2020.eu
Ralf Ohnmacht(1)
Walter Haslinger(1), tel.: +43 7416 52238 20, email: walter.haslinger@bioenergy2020.eu
*corresponding author
1) BIOENERGY 2020+ GmbH, Gewerbepark Haag 3, 3250 Wieselburg-Land, Austria,
   fax: +43 7416 52238 99
2) Division of Energy Engineering, Luleå University of Technology, SE-971 87 Luleå, Sweden

About 30% of the total energy use in Austria is dedicated to heating purposes and hot water provision. During the last decade, biomass boilers had a major comeback due to increasing prizes for fossil fuels and the renewable character of the fuel. In 2009, 20.000 biomass boilers with a nominal thermal output up to 100kW were installed in Austria. However, conventional small scale biomass boilers reach only about 73% to 89% energy efficiency based on the gross calorific value [1]. This disadvantage originates mainly from the flue gas temperature. The sensible heat and, more importantly, the latent heat of water are lost to the ambient. Accordingly, a module being able to transfer the heat of condensation to the return flow strongly enhances the efficiency.

In this paper we present the concept of active condensation, which combines a condensation device and a heat pump. In a first step the flue gas is cooled down until almost complete condensation of the water vapor. Afterwards a heat pump transforms the recovered low temperature energy to the temperature of the return flow. This technology can be used independently of the return flow temperature, and therefore is particularly important for retrofitted houses, where the return flow temperature is often higher than the condensation temperature of the flue gas.

To evaluate the suggested system, we model each component by mass and energy balances in the Matlab/Simulink environment. Each component model is based on physical laws or measurement data from available components of cognate technologies. We will present efficiency factors and an economic analysis for different heat pump powers and return flow temperatures. Subsequently we will estimate optimal design criteria.

In Europe, biomass is one of the broadly available renewable sources for residential heating and hot water production. Today 84% of the total energy consumption of households in the EU-27 is required for heating (70%) and hot water provision (14%) [2]. During the last decade, biomass boilers have made a major comeback due to increasing prices for fossil fuels and the renewable character of the fuel. In particular the introduction of automatic boilers based on pellet and wood chips has made biomass boilers convenient to use and thus a low CO₂ alternative to fossil fueled ones. In fact, from
2004 to 2010 boiler sales increased by 84% in the EU [3]. The total number of biomass boilers sold in 2007 is estimated at 8 million. For example, in Austria 8,000 pellet, 8,000 log wood, and 4,000 wood chip boilers with a nominal thermal output up to 100kW were installed in 2009 [4].

![Fig. 1](image-url)

**Fig. 1.** Maximum achievable energy efficiency based on the gross calorific value for different flue gas temperatures. Numbers indicate fuel water content.

Today small-scale biomass boilers for heating and hot water provision are highly efficient. State of the art boilers reach efficiencies of 85% to 89% (pellets) and 73% to 81% (wood chips) based on the cross calorific value [1]. Nevertheless these boilers do have losses which mainly originate from the thermal energy of the flue gas, which leaves the boiler at temperatures of 120-150°C. These losses can be divided into the sensible heat of the flue gas and the latent heat of the water vapor in the flue gas. The sensible heat losses depend nearly linearly on the temperature of the flue gas. In contrast, the latent heat can only be recovered if the flue gas is cooled down below the dew temperature of the flue gas. The dew point can be located at temperatures between 40-60°C (see figure 1).

**Technical concept**
The difficulty lies in the concept, how to use this low temperature heat for heating purposes. Since most existing buildings have a return flow temperature that is higher than the above mentioned dew point temperatures, one cannot use the heat directly. Therefore, we introduce the concept of active condensation. This concept combines a condensation device and a heat pump. In the condensation device, the heat from the flue gas is recovered at a low temperature (~25°C) independently of the return flow temperature. The heat pump is used to upgrade the thermal energy from the recovery temperature to the higher return flow temperature. Thus, active condensation has the advantage that it can be used for retrofitting older buildings, where the return flow temperature is high.

The proposed solution is a system that combines a quench and a heat pump (see Fig. 2). In a quench cold water droplets are injected into hot flue gas. Due to the high surface area of the water droplets a fast energy and mass transfer between water and flue gas takes place. As a result the flue gas is cooled down while the water droplets are heated up. This water provides the energy source for the heat pump. In the heat pump, the water is cooled down and circulated back to the quench. Meanwhile, on the hot side of the heat pump, the return flow is heated up before it enters the boiler. Thus the thermal output of the system (boiler and active condensation) is higher without increasing the fuel
input. However, we called the concept “active condensation”, because an additional electric energy is necessary.

![Diagram of the investigated active condensation system](image)

**Fig. 2.** Scheme of the investigated active condensation system. Shows the active condensation system with heat pump and quench including the connections to the boiler: fg – flue gas, rf – return flow, cw – circulating water, sw – supply water

**Outlook**

We will present a mathematical model with mass and energy balances. Our aim is to represent the interactions between all components (heat pump, boiler, quench). The heat pump is modeled with COP (coefficient of performance) data from existing market-available components. From this data the Carnot efficiency, which is the COP of the heat pump divided by the maximum thermodynamic possible COP, is estimated. As the Carnot efficiency changes with operating temperatures, it reproduces heat pump behavior quite well. The boiler is modeled with a simple energy balance to obtain the adiabatic temperature, which depends on the fuel composition and the excess air ratio. In turn, boiler efficiency is determined according to the flue gas outlet temperature, neglecting other sources of thermal losses. Quench outlet is assumed to be in thermodynamic equilibrium. The amount of condensed water is eventually calculated as a function of the flue gas flow, the water vapor in the flue gas, the water mass flow and the temperatures of all flows. All three components are connected to the system model. Based on this model we perform simulations to identify the heat gain as well as the electric input for different parameter variations. The varied parameters are mainly the return flow temperature and the water content of the fuel. An example of the energy efficiency depending on the fuel water content is given in figure 3. Furthermore we will critically investigate under which conditions the integration of an active condensation device lowers the total fuel consumption, taking into account the specific fuel consumption of the electrical mix in Austria.
Fig. 3. Energy efficiency (fuel & electricity) of the system for given parameters: flue gas temperature after the boiler 120°C, return flow temperature 60°C, quench outlet temperature 25°C. [5]

Finally, we will assess the economic viability for different boiler and heat pump powers. This will be done by estimating the prize for the active condensation device based on the prizes for available components. Then the prizes for biomass and electricity will be compared and the payback time of the active condensation device can be calculated. Thus, we will identify possible applications. In summary, we are able to give a thermodynamic and economic evaluation of the active condensation device, showing under which circumstances the integration will lower the total energy consumption and give benefits to the customer.

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