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Steam Accumulator Integration for Increasing Energy Utilisation of Solid Biomass-Fuelled CHP Plants in Industrial Applications

Matthias Stark[a,*], Matthias Philipp[a], Abdessamad Saidi[a], Christoph Trinkl[a], Wilfried Zörner[a], Rick Greenough[b]

[a]Technische Hochschule Ingolstadt, Institute of new Energy Systems, Esplanade 10 85049 Ingolstadt, Germany
[b]De Montfort University, Institute of Energy and Sustainable Development, The Gateway Leicester, LE1 9BH UK
matthias.stark@thi.de

Process steam, which shows a wide scope of utilization in various industrial processes, is currently predominantly generated by fossil fuels. An instant measure in order to reduce greenhouse gas emissions is, therefore, to substitute fossil fuel-based steam production by biomass combustion plants in Combined Heat and Power (CHP) operation. Because of the typically discontinuous steam demand, CHP steam turbines, however, are facing various operational challenges. In this context, a steam accumulator enables decoupling of generation and demand. Using a thermodynamic simulation model based on MATLAB/Simulink, the optimization potential for the plant operation to meet the different operational requirements is demonstrated.

1. Introduction

1.1 Motivation

Steam-driven energy systems are widely used in chemical (Smith et al., 2005), building materials (Bühler et al., 2016), pharma (Sommer et al., 2013), pet food (Pessel et al.,2016) and nutrition industries (Schumm et al., 2016). To achieve the COP21 (Paris) greenhouse gas emission targets, the industries' conventional fossil fuel systems need to be replaced (Phillip et al., 2017). Using biomass combustion plants for steam production has an immediate effect on emission reduction. Therefore, there are already numerous industrial processes receiving process steam from biomass CHP plants. Due to fluctuating steam demands turbines cannot be driven at their optimum operation point. This issue affects several biomass plants in Germany. This paper, therefore, describes an approach based on a steam accumulator to increase solid biomass utilization for optimized power plant operation. The simulation model generation is based on measurement data from a real biomass combustion plant supplying a pharma site.

1.2 Problem statement

Industrial steam load profiles often show high fluctuations. In many cases, the amount of required steam is variable, depending on the needs of the production process. Unpredictable drops and rises of the demand occur on short-term basis.

Due to the inhomogeneous properties of biomass, biomass plants' furnaces and steam boilers are typically designed to generate a constant amount of live-steam. Therefore, quick load changes overextend the capacities of most biomass CHP plants. Almost constant amounts of live-steam are generated and fed into the extraction turbine. While the turbine expands the live-steam down to a pressure level of below 0.01 MPa, a side stream may be extracted to supply heat or steam for a process application. The amount of this extraction steam is variable, while the reaction speed is limited by design specifications of the turbine.

Figure 1 shows a typical steam consumption chart, where the power generation of the generator is shown depending on the amount of live-steam and extraction steam. The mass flow of the extraction steam is supposed to be between $\dot{m}_{min}$ and $\dot{m}_{max}$. In the illustrated example ($\dot{m}$ = 6 kg/s), the range of the extraction has to be

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between $\dot{m}_{max}$ = 5.27 kg/s and $\dot{m}_{min}$ = 1.66 kg/s. In case of a mass flow below $\dot{m}_{min}$, the turbine has to be bypassed or excess steam has to be led directly into the condenser. Both approaches cause significant steam energy losses. Moreover, short-term drops of the process steam demand result in a risk of an emergency turbine shutdown.

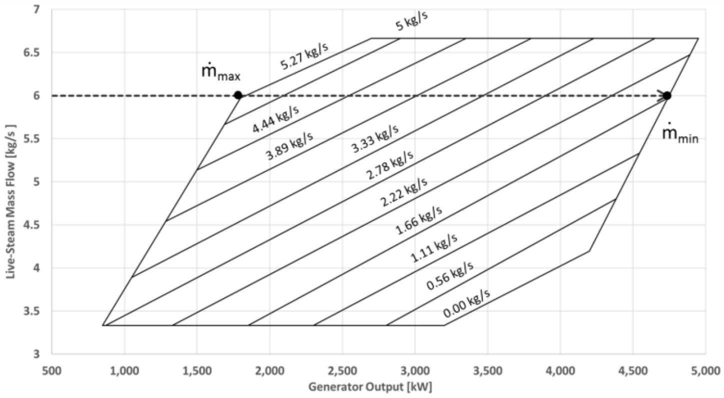

Figure 1: Steam demand diagram

Throttling the extraction mass flow reduces the frequency and gradient of the drops. This behaviour was observed at the reference plant. These have, due to the capacity of the steam distribution line, a delayed effect on the extraction point of the turbine. Therefore, throttling the extraction represent a suitable measure to increase this delay, hence, reduce the gradients and turbine shut downs. Throttling is a feasible measure to stabilize the operation of the turbine, however, it leads to a poor steam coverage ratio. To identify the impact of the steam accumulator the biomass coverage ratio is introduced Eq(1). This value quantifies the share of process steam supplied by the biomass plant.

$$biomass\ coverage\ ratio = \frac{m\ (steam\ from\ biomass\ plant)}{m\ (total\ steam\ demand)} \tag{1}$$

To meet these challenges, the aim of the research project is to find a solution for a stable turbine operation without throttling the extraction mass flow.

2. Steam accumulator for increasing energy utilisation

To overcome the challenges caused by volatile steam demand, a steam accumulator is a feasible option. The aim of this concept is to decouple the steam extraction from the steam supply via a storage. Figure 2 describes the interconnection of the plant and an industrial facility.

In its current state (a), the required process steam is directly taken from the extraction turbine. The integration of a steam accumulator (b) decouples the extraction point from the process steam consumer. Therefore, the extraction steam is led into the steam accumulator from where the process steam is taken to supply the consumer.

Charging of the accumulator with a constant mass flow happens at the same time as supplying process steam to the industrial consumer. In addition to the smoothening of the extraction steam mass flow, the steam accumulator offers the opportunity to meet peak demands for short periods. Therefore, the share of fossil steam generation from peak load boilers can be reduced even further.

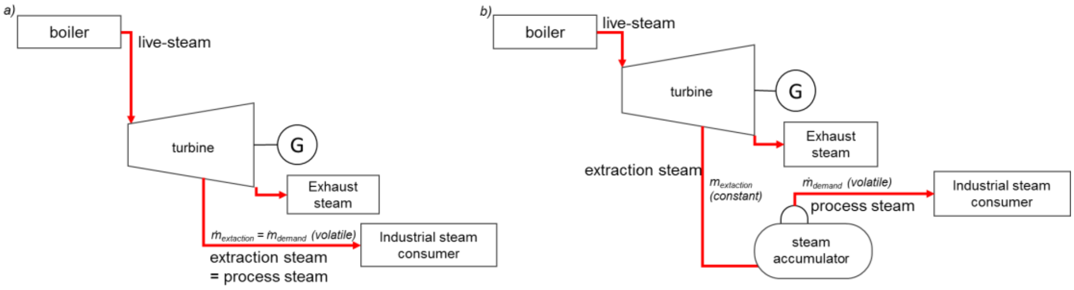

Figure 2: Interconnection of the steam accumulator

Biglia et al. (2017) investigated the implementation of a steam accumulator for industrial steam processes. They simulated the performance of the accumulator for peak loading of a fossil boiler in the food industry and concluded a profitability in a wide set of industrial applications. Stark et al. (2017) discussed the utilization of steam storage technologies regarding their implementation in biomass combustion plants with the aim of flexible, demand-oriented power generation. They stated suitability of improving the process steam supply by using steam accumulators (Stark et al., 2017).

The steam accumulator, also known as 'Ruths accumulator', represents an established technology in use since the 1930s. This device allows heat storage in the form of liquid water. Even if the storage is completely discharged, a liquid phase still remains inside. Superheated or saturated charging steam is directly injected into the liquid phase and immediately condensed. During charging, the pressure and the temperature inside the steam accumulator, which correspond to the evaporating parameters of the liquid phase, is increasing. By pressure decrease via opening of a valve in the discharge line, a flash evaporation is initialized. Therefore, controlled by the pressure reduction, saturated steam is generated immediately.

In the last decades, research on steam accumulators was focused on applications in solar-thermal power plants. Within this application, coupling of steam generation and steam accumulator is an effective solution to keep the plants in operation during the night. Improved concepts for steam accumulators (Steinmann et al., 2006) and new technologies (Gil et al., 2010) were developed for this case. However, for the utilization on industrial scale, the steam accumulator still represents the optimum solution, due to its ability to generate steam immediately.

3. Methodology

To investigate the influence of the steam accumulator on the afore-mentioned supply concept, mathematical models of the CHP plant and the steam accumulator are developed in MATLAB/Simulink. Measurements from an existing biomass CHP plant in Germany, which supplies an industrial facility with steam and heat, are used for validation. For this study, irrelevant components like combustion, boiler and condenser are neglected because of their low influence on the results. Boundary conditions between numerical model and remaining systems (live-steam supply and process steam demand) are fed into the simulation as measurement values. Figure 3 shows the layout of the simulation model and the input of measurement data.

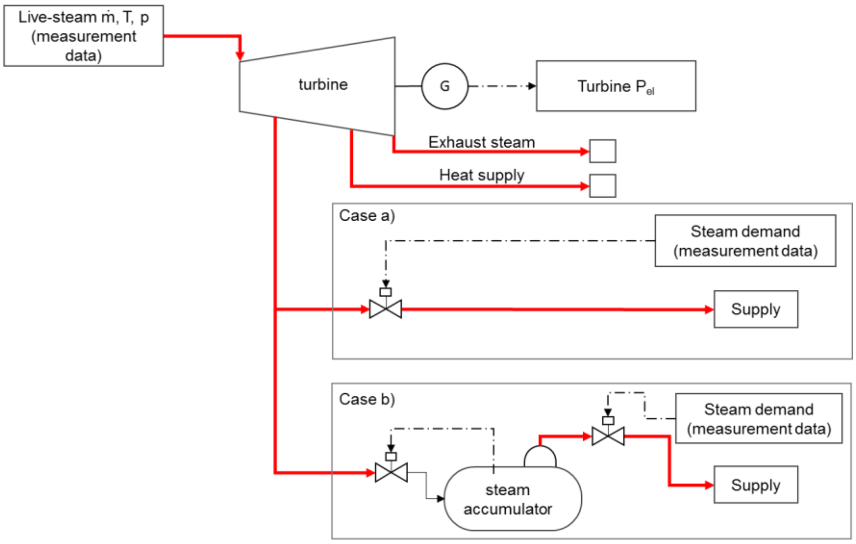

Figure 3: Simulation layout

The considered plant has an additional steam extraction for heat supply, which shows a low and nearly constant behaviour. Therefore, it is not connected to the steam accumulator. For this level of detail, the following simplifying assumptions were made:

- neglect of heat losses in the accumulator and piping,
- neglect of pressure losses and steam leakages.

Especially the thermal loss of the steam accumulator usually has a significant impact on the overall efficiency. Due to the short term operations (charge/discharge during minutes or seconds) and the thermal insulation, the heat losses inside the storage are neglected for the present issue.

The model concept allows a comprehensive sensitivity analysis including various process parameters and plant configurations. By analyzing different plant configurations and steam load profiles, various cases can be considered within the simulations, where the model can be used as a tool for dimensioning steam accumulator systems. The simulation can be performed in two optional scenarios, with and without a steam accumulator, which allows a comparative evaluation between case a) and bThe configuration of the biomass plant is set according to the reference plant: rated thermal capacity of 21.4 MW_{th} and live-steam operation parameters of 6.75 kg/s, 460 °C and 6.3 MPa.

3.1 Turbine model

The aim of the turbine model is to provide a detailed calculation of part load scenarios, the focus is on part loads caused by varying steam extraction mass flow. The improved turbine hardware model (THM) formulation was chosen as an advanced modelling approach for simple turbines (Lou et al., 2011). A complex multi-extraction turbine model can be made up of n+1 simple turbines with fixed inlet and outlet pressure, where n defines the number of controlled extractions. Based on the common thermodynamic calculation Eq(2) for the turbine inlet and outlet parameters, the part load behaviour of the turbine is characterized by the isentropic efficiency $\eta_{t,z}^{is}$. The improved THM enables an estimation of the isentropic efficiency based on design and the operation mass-flow of the single turbine parts Eq(3). Hence, the part load effect of the extraction points is taken into account. The regression coefficients α (0.1854 MW), β (0.0433 MW/Pa), γ (1.2057) and λ (0.0075 MPa^{-1}) for simple turbines were used in Eq(4) and Eq(5).

$$h_{t,z}^{out} = h_{t,z}^{in} - \eta_{t,z}^{is} * \Delta h_{t,z}^{is} \tag{2}$$

$$\eta_{t,z}^{is} = \frac{6}{5B} * \left(1 - \frac{A}{\Delta h_{t,z}^{is} * M_{t,z}^{dn}}\right)\left(1 - \frac{M_{t,z}^{dn}}{6M_{t,z}^{in}}\right) \tag{3}$$

$$A = \alpha + \beta * p_{t,z}^{in} \tag{4}$$

$$B = \gamma + \lambda * p_{t,z}^{in} \tag{5}$$

The plant's turbine is operated at an input pressure of 6.3 MPa, while the extraction points are set at 1.75 MPa (process steam), and 0.3 MPa (heat). For the exhaust pressure, a value of 0.0071 MPa is assumed. The model operation is based on the steamflow chart of the turbine (Figure 1).

3.2 Steam accumulator

Regarding the steam accumulator, several model formulations are available. These approaches can be categorized according to the consideration of equilibrium or non-equilibrium conditions between the liquid and the vapour phase. The so-called equilibrium models assume the same pressure and saturation temperature in both phases, which allows a calculation of the complete thermodynamic state of the steam accumulator as a function of pressure or temperature.

The non-equilibrium formulation represents a more detailed and complex type of modelling. This approach considers different temperature and pressure gradients in liquid and vapour phase.

To ensure valid simulation parameters, experimental data such as evaporation and condensation relaxation times are required. Those parameters depend on input and boundaries conditions such as storage dimensions and pressure. Since these parameters are not available for the present research issue, the simplified equilibrium model is chosen Eq. (6). The simulation of Stevanovic simulation shows a pressure deviation of 5-7% between Equilibrium and Non-Equilibrium model. Stevanovic et al. (2015) describe the model equations in more detail.

$$\frac{dp}{dt} = \frac{(\dot{m}h)_{1B} + (\dot{m}h)_{2B} + \left(\frac{\frac{rV}{M}}{v'' - v'} - h\right)(\dot{m}_{1B} + \dot{m}_{1B})}{M\left(\frac{dh'}{dp} + \frac{\frac{V}{M} - v'}{v'' - v'}\frac{dr}{dp} - \frac{r}{v'' - v'}\frac{dv'}{dp} - r\frac{\frac{V}{M} - v'}{(v'' - v')^2}\frac{d((v'' - v'))}{dp}\right) - V} \tag{6}$$

In case of the present simulation, the total steam accumulator volume is set at 52 m^3. The pressure outlet on the extraction is 1.75 MPa, the required pressure for the process is 1.4 MPa. Assuming a maximum pressure loss of 0.05 MPa in the steam distribution, the pressure drop of the steam accumulator is set at 0.30 MPa, resulting in a thermal capacity of 455 kWh (~430 kg_{steam}). The configuration of the reference plant enables the use of this pressure drop without increasing the extraction pressure. To transfer this concept to further plant configurations, it might be necessary to operate a turbine with higher extraction pressures. The resulting significant reduction of the power generation has to be considered.

4. Simulation results

In the first simulation, the effect of the steam accumulator on the extraction mass flow is investigated. In Figure 4, the measurement of the extraction mass flow is shown over a time range of 120 h. During this period, the amount of extraction steam mass flow falls below the minimum value of 2.3 kg/s more than 30 times. In total, an amount of 1,313 t process steam is supplied. To avoid turbine turndown and operation problems, a maximum extraction mass flow was set at 3.2 kg/s at the reference plant.

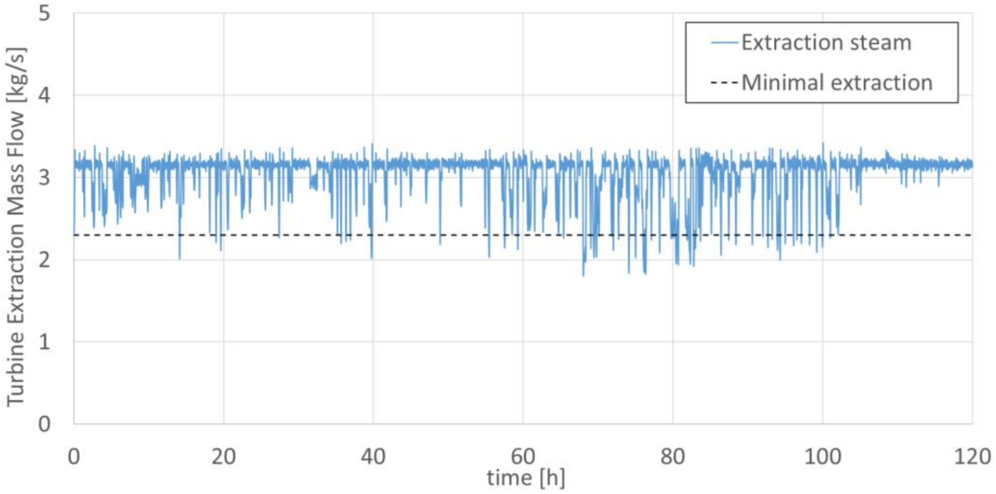

Figure 4: Extraction mass flow without storage (measured data)

By performing the simulation with a steam accumulator, a significant difference is detected as shown in Figure 5. The amount of extraction steam mass flow does not fall below the minimum value and a significant increase of the operation stability is realized. Thus, the use of the steam accumulator significantly improves the operation of the turbine. In this simulation, the total amount of extraction steam was the same as in Figure 4. The power generation is not impacted significantly by the use of a steam accumulator (see Table 1). Seen in a longer term perspective, the stable operation will reduce the effort for maintenance and delay the aging process with its corresponding efficiency losses.

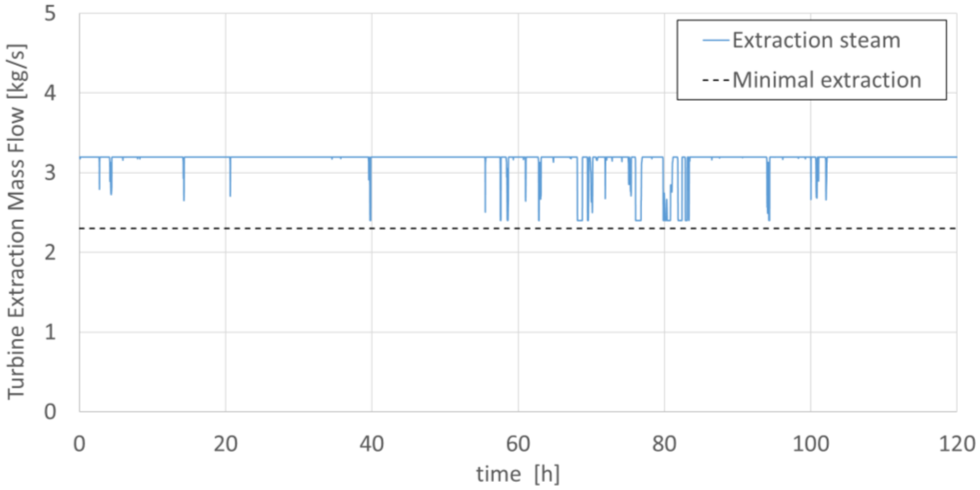

Figure 5: Extraction mass flow with storage (simulation)

Further simulation is carried out to determine the increase of the bio mass coverage ratio. For this purpose, the option of throttling the extraction steam mass flow (3.2 kg/s) is disabled, wherefore a maximum steam mass flow of 4.16 kg/s can be extracted. Within this simulation, the bio-coverage ratio is increased up to 69 % (from 52.5 %). The results of the three simulation cases are listed in Table 1. Furthermore, the simulation shows that peak loads are supplied by the steam accumulator. For short periods, steam demands even higher than the maximum extraction of 4.16 kg/s can be supplied.

Table 1: Results of the simulation (120 h)

Case	1	2	3
Steam accumulator	None	52 m²	52 m²
Max. extraction	3.2 kg/s	3.2 kg/s	4.16 kg/s
Power generation	414.1 MWh	421.4 MWh	346.5 MWh
Biomass coverage ratio	52.5%	53.7%	69%
Steam supply	1,137 t	1,163 t	1,514 t

5. Conclusions

The simulation results determine the advantages of the integration of a steam accumulator in an extraction turbine system. This developed concept allows to avoid the demand of throttling the steam extraction, which is discussed in the introductory problem statement. The proposed measures enabled significant stabilization of the extraction mass flow. In addition to stabilizing the turbine operation, the mass flow of the extraction can be increased. Depending on the storage size, short-term peak loads can be supplied from the steam storage. The coverage ratio of steam from biomass CHP plant can be significantly increased depending on the demand profile and the accumulator specifications.

Advanced control strategies have the potential to further increase the biomass coverage ratio. To evaluate the technical feasibility of the developed design, an experimental validation of the simulation results is required. Measurements of process parameters from actual steam accumulator operation in industrial facilities can provide a reliable system validation.

Regarding flexible power generation, the presented steam accumulator design contributes to an increase of the potential of industrial biomass CHP for demand-oriented energy supply.

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