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Design Parameters of Steam Accumulators for the Utilization in Industrial Solid Biomass-Fuelled CHP Plants

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Fossil fuels are currently used to generate the major part of process steam for industrial facilities. An established approach for the sustainable substitution of fossil resources is the supply from solid biomass-fuelled combined heat and power (CHP) plants. However, current designs of biomass CHP plants usually raise only a share of the total steam demand (fossil-fuelled boilers supplying the rest), due to limits in their design. A steam accumulator represents a promising device to increase the share of steam generated from biomass. Based on a simulation model developed for the specific application, this paper confirms the positive effect of a steam accumulator on the biomass coverage ratio (BCR). An increase from 82% up to 95% is demonstrated Furthermore, relevant design parameters such as the charging massflow and the operational pressure difference are identified as key design parameters for the steam accumulator.

1. Introduction

1.1 Motivation

Steam-driven processes are widely in use throughout the industrial sector, in industries such as chemicals (Smith et. al, 2005), building materials (Bühler et. al, 2016), pharmaceuticals (Stark et. al, 2018) and pet food (Pessel et al., 2016). The major share of the required steam is provided via steam boilers, which are predominantly driven by natural gas. To achieve the COP21 greenhouse gas emission targets, these fossil fuel-based supply systems have to be replaced. Among the available alternatives, solid biomass-fuelled combustion plants for combined heat and power (CHP) production show potential for a significant reduction of CO_2 emissions.

1.2 Problem statement

Industrial facilities are characterised by a variety of different energy demand patterns and overlapping production processes, leading to a highly variable demand for steam, which must be handled by the steam generators.
Even though a degree of smoothing of these demand profiles is possible through steam demand management and production planning, in most of the applications fluctuating demand profiles cannot not adjusted sufficiently due to sensitive processes, supply chains, economic reasons and technical boundaries. Therefore, quickly reacting steam generators are required for the supply of industrial process steam.
Solid biomass-fuelled CHP plants for the steam supply of industrial facilities are typically equipped with extraction turbines. Depending on the pressure level required, steam can be extracted from different turbine stages, allowing the plants to handle variations in steam demand. Nevertheless, the turbines have to be operated between a minimum and maximum extraction massflow ($\dot{m}_{ex.min}$ and $\dot{m}_{ex.max}$ respectively) depending on the specific turbine design. A steam demand below $\dot{m}_{ex.min}$ increases the risk of a turbine shutdown, as discussed in Stark et al. (2018).

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Figure 1 shows an example of a load profile of a pharmaceutical production facility supplied by a solid biomass-fuelled CHP plant (left diagram). The plant is located in southern Germany and has a rated thermal capacity of 21.4 MW_{th}. Long term data collection has been carried out here, and the data are used in this study.
Due to the above mentioned massflow limitations, the biomass CHP plant can only supply a share of the total steam demand (see Figure 1, right diagram). Bypassing the turbine is one solution to handle the turbines extraction limitations. However, this approach decreases the plants power production and led to an utilisation of high-exergy live-steam for low-exergy process steam applications. Therefore, a concept to avoid turbine bypass is required.

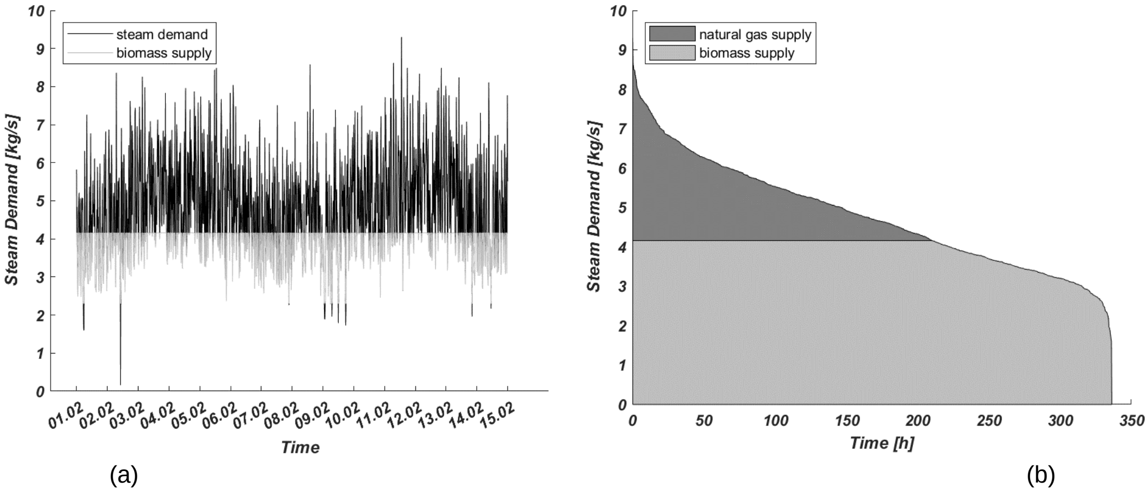

Figure 1: Steam demand profile for a pharmaceutical facility shown as time series (a) and load duration curve (b).

Stark et al. (2018) introduced the concept of a biomass coverage ratio (BCR) in order to quantify the share of total steam demand provided by biomass-based heat (Eq.(1)).

$$BCR = \frac{m_{steam\ from\ biomass\ plant}}{m_{total\ steam\ demand}} \tag{1}$$

In the case shown in Figure 1, the solid biomass-fuelled CHP plant is able to reach a BCR of 82 %, while the remaining 18% is provided by a natural gas boiler. Quantifying the degree of fossil fuel substitution, the BCR also represents a performance indicator for CO_2 emission savings. Therefore, from a greenhouse gas emission saving point of view, an increase of the BCR is desirable.

1.3 Steam accumulator integration

In order to increase the BCR in industrial processes, the integration of a steam accumulator, which is in fact an established storage concept, represents a promising approach (Stark et. al, 2017). A serial connection of the accumulator between turbine extraction and industrial steam consumer enables steam buffering according to the process demand (see Figure 2). This allows the steam accumulator to supply additional peak loads and refill during falls in demand.
The focus of former research work (Stark et. al, 2018) was an in-depth analysis of the steam accumulator's impact on the turbine in terms of efficiency and operational stability. The main issue that this work addressed was avoidance of the reduction of extraction mass flow below the minimum extraction point. Supplementing this, the work described here focuses on steam accumulator operation from a supply perspective and based on this, the derivation of relevant parameters for the steam accumulator design. The application of steam accumulators for industrial utility systems is a well-described topic. However, they are mainly used in conventional steam supply cases. Combining a steam accumulator with a biomass CHP process, especially with the limitation afflicted extraction turbine as well as the power focused operation of the CHP plant, represents a novel approach.

2. Simulation study

To analyse the industrial process, the Matlab/Simulink based plant model (see Figure 2), introduced by Stark et al. (2018) is applied to the supply chain. The steam demand profile of the facility is used as input data for the operation of the model. As a first step, the operational behaviour of the system including the steam accumulator is analysed. Subsequently, several parameters are varied in order to investigate their impact on the entire system. The simulation model represents the solid biomass-fuelled CHP plant used at a pharmaceutical facility (cf. Figure 1). The model is parametrised and validated with measured data from this system. In addition, the design and operational parameters of this plant as well as the load profile of the facility are used for the calculations. The simulated results of conventional operation show an average error of 5% for the extraction massflow and 3% of the turbine power generation, compared with measured data.

2.1 Model structure

The developed model is designed for the calculation of two different cases (Figure 2). Case A represents the conventional operation mode without steam storage devices while case B describes the operation when a steam accumulator is included. The steam turbine, steam accumulator and control valves represent the main sub-systems of the simulation model. Further plant components such as the boiler are not considered. As the measurements show, their influence on the whole system were negligible. The measured live-steam generated in the plant's boiler is set as an input signal for the simulation.

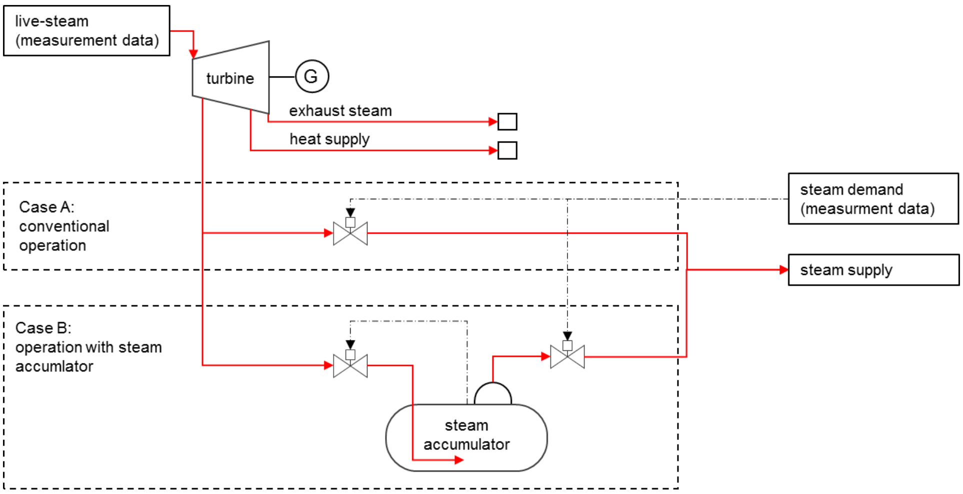

Figure 2: Structure of the simulation model.

Steam Accumulator

For the analysis of the steam accumulator, the equilibrium model of Stevanovic et al. (2015) is applied. More detailed non-equilibrium modelling approaches are available in literature (e.g. Sun et. al, 2015), but reliable experimental data for specific model parameters are lacking. For this reason, Biglia et al. (2017) proposed the equilibrium model instead of the non-equilibrium model as a suitable tool for verifying the operation conditions of a steam accumulator. In addition, this model was applied in various studies in which steam accumulators are integrated into steam processes within the food industry (Biglia et al., 2017). Stark et al. (2018) give a detailed description of the applied model.
The capacity of the steam accumulator is defined as the mass of steam that can be stored and discharged. While steam accumulators generate saturated steam, the extraction steam is usually superheated. Hence, the charging steam has a higher energy density compared to the discharge steam causing a difference between charge and discharge capacity. Besides the steam accumulator volume, the pressure difference between the charge and discharge pipe also has an influence on the capacity. Due to the serial connection, the steam accumulator can be charged and discharged at the same time. A detailed description of the model is given by Stark et al. (2018).

Turbine model

The improved turbine hardware model (THM) formulation is used for the analysis of the plant's turbine (cf. Lou et al., 2011). This modelling approach for simple turbines can also be used to simulate complex multi-extraction turbines with various stages. The power output of the single turbine stages are calculated as a function of massflow, enthalpy difference and isentropic efficiency. In existing turbines, the turbine dimension defines the isentropic efficiency, which is changing during part-load operation. Based on model parameters, the ratio of design massflow, recent massflow as well as the input and output pressure levels; the THM calculates the isentropic efficiency. Depending on the turbine design, each extraction step is limited to a maximum ($\dot{m}_{ex,max}$) and minimum ($\dot{m}_{ex,min}$) extracted massflow. The model equations as well as the regression parameters are illustrated in Stark et al. (2018).

Control Strategy

For of the control valves, a massflow control algorithm is implemented. The charging controller reduces the extraction massflow linearly from $\dot{m}_{ex,max}$ to $\dot{m}_{ex,min}$ depending on the accumulator pressure as the main control value. For the discharge, the massflow is set equal to the demand, limited to a maximum discharge massflow which depends on the steam accumulator design. At minimum pressure the discharge is stopped completely.

2.2 Case study

The steam demand measured in the industrial facility does not show any seasonality, therefore a period of 14 days in February 2016 is selected as a representative demand profile for the simulations. During this period, a total steam demand of 5,801 t at a pressure of 1.4 MPa is required.
Furthermore, a constant live-steam massflow of 6.53 kg/s at a temperature 470 °C and a pressure of 6.5 MPa is considered. A three-stage extraction turbine with extraction stages at 1.75 MPa (process steam extraction) and 0.3 MPa (heat extraction) is used. In the last turbine stage, the steam is released at a condensation pressure of 7 kPa. Following the turbine datasheet, the design massflow (a required parameter for the turbine model) is set at 6.53 kg/s in the first stage and 2.2 kg/s in the following stages 2 and 3. Related to the live-steam massflow into the turbine, the maximum extraction ($\dot{m}_{ex,max}$) is 4.16 kg/s, while the minimum extraction ($\dot{m}_{ex,min}$) is 2.30 kg/s. Additional steam extraction (e.g. for the CHP process or heat supply) is not considered. Furthermore, pipe losses of 0.05 MPa between turbine and steam supply are assumed. Hence, the steam accumulator has a usable pressure range of 0.3 MPa between extraction and steam supply. This operation enables a storage density of 17 kg/m³. Three gas boilers with a full-load generation of 5.2 kg/s each are utilised for the peak loads and reserve. A steam demand below the minimum generation of 0.75 kg/s can be compensated by piping system.

3. Simulation results

Figure 3 shows the results of an initial simulation with a steam accumulator volume of 100 m³. In case A, the process steam supply is limited by the turbines $\dot{m}_{ex,max}$. This limitation is exceeded in case B, where the steam accumulator integration and resulting temporary additional steam supply enables a significant increase of the BCR from 82 % to 90 %.

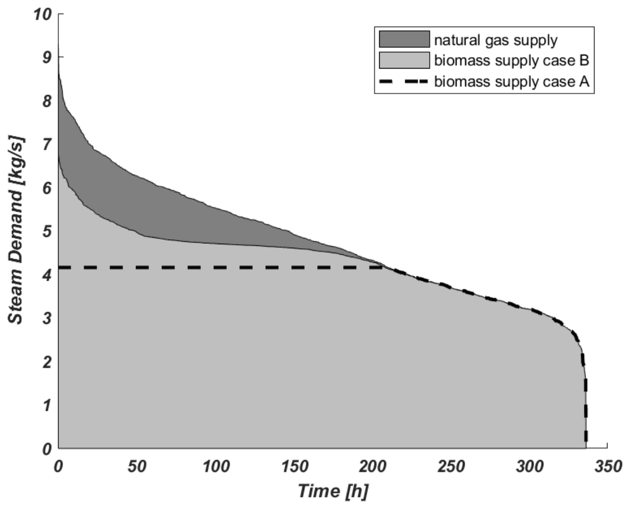

Figure 3: Sorted load curve for simulations of conventional operation (case A) and operation with steam accumulator volume of 100 m³ (case B).

For a more detailed analysis of the system behaviour, Figure 4 shows a process diagram for a 20 h operation period for both cases. The upper part illustrates the steam demand and the supply of the biomass plant for both cases. On the lower part, the pressure level of the steam accumulator illustrates the load level of the storage. Maximum pressure (1.75 MPa) is equivalent to a fully charged storage while minimum pressure (1.45 MPa) represents a discharged storage. In case A, the peak loads are not supplied due to the limited maximum extraction of the turbine. By contrast, a steam supply higher than $\dot{m}_{ex,max}$ is achieved during peak loads in case B. As well as storage capacity, the BCR depends on further system parameters. Comparing demand peaks 1 and 2 in Figure 4, we can see that the total amount of steam demand is nearly equal. However, while peak 2 is supplied entirely by steam from biomass combustion, peak 1 requires additional external steam. The gap between demand and supply for peak 1 is caused by the recurring discharges and short regeneration times within the period of 16:00 to 20:00 h. Therefore, it is not only the storage capacity, but also the charging rate as well as the demand profile that have a significant influence on the supply.

In addition to the demand peaks, the troughs can also be buffered. Trough 1 shows a demand below the $\dot{m}_{ex,min}$. In case A, the extracted steam mass flow is higher than the demand and therefore has to be bypassed. In case B, this excess steam can be stored completely in the steam accumulator. By storing excess steam during demand troughs, the risk of emergency turbine shutdowns and the losses caused by bypassing are minimised (Stark et al. 2018).

A further effect is recognised in the period after sink 1, where a relatively small part of the following peak is supplied, even though the storage is fully charged. The charge controller, using the pressure of the steam accumulator as a control signal, causes this effect. As the pressure level at the beginning of the discharge process is at maximum, the discharge massflow is at its minimum. During the supply of the peak, the accumulator pressure decreases but extraction (charge) massflow is only increased slowly. The aim of this control is to avoid storage overloads, but in this case, it limits the discharge capacity. A solution for this effect would be the inclusion of the demand gradient into the control algorithm. This could optimise the utilisation of the storage and therefore the BCR.

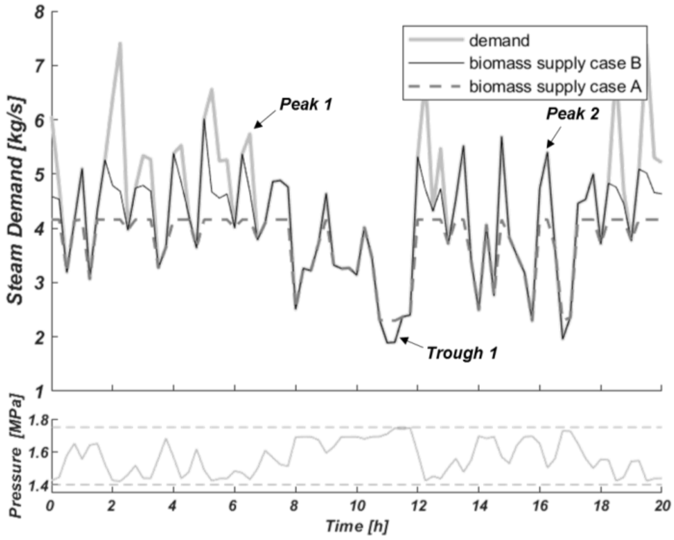

Figure 4: Process diagram for a 20h operation period (simulation).

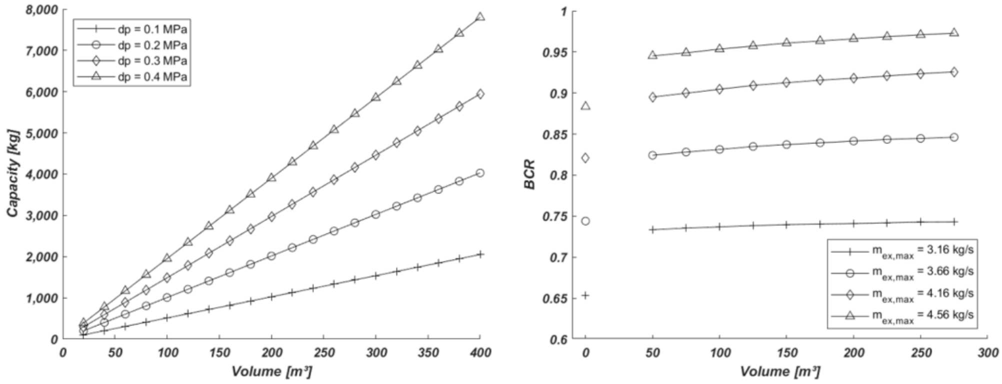

Figure 5: (a) Variation of pressure drop and volume. (b) Variation of $\dot{m}_{ex,max}$ and volume.

Since not only the volume but also the charge/discharge rates as well as the pressure drop affect the storage behaviour, the influence of these parameters is investigated in more detail. An initial parameter study is performed to identify the relation between pressure drop and storage volume (Figure 5a). The analysis shows that an increase of the pressure drop has a more significant impact on the capacity than increasing the volume of the steam accumulator.A further parameter study investigates the influence on the biomass coverage ratio for various capacities and extraction mass flows $\dot{m}_{ex,max}$. Figure5b illustrates a significant increase of the BCR by increasing $\dot{m}_{ex,max}$, which also has a more significant impact than increasing the storage volume alone. Both parameters, the pressure drop and the maximum extraction $\dot{m}_{ex,max}$ depend on the turbine design, the industrial process and other various aspects. Hence, they cannot be seen as design parameter only for the steam accumulator system. Nevertheless, for the design of these kind of steam supply systems, the approach of utilizing a higher pressure drop and extraction massflow $\dot{m}_{ex,max}$ to improve the BCR or reduce the required accumulator volume, has to be considered.

4. Conclusions

By the integration of a steam accumulator into a biomass CHP steam supply system, the BCR and thereby the fossil fuel consumption can be increased. The design process for accumulator systems should consider not only the storage capacity in terms of the volume, but also available pressure levels, the design parameters of the turbine's extraction as well as load profile and charging/discharging rates since these also affect the operation significantly.

Hence, it is necessary to perform a detailed analysis of the process and the operational behaviour of an industrial facility to ensure a valid decision concerning whether a steam accumulator can contribute to technical, ecologic and economic efficiency of the whole system. In the present study, only a single plant composition with a selected demand profile of one specific period is analysed. Despite this, the results provide an understanding of the fundamental behaviour and the analysis can be adapted to different supply systems. In general, each industrial facility has its very individual steam demand profile, which has to be investigated in detail for the integration of steam storage devices.

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