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Process modelling and technology evaluation in brewing

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ABSTRACT

To reach an integrated sustainable production site, it is important to analyse effects of technology changes. A "brewery model" has been developed which allows process modelling of a brewing facility. Besides the comparison of specific demand figures, it allows a holistic view of the production site and most importantly the modelling of energy demand profiles. Energy demand profiles in brewing vary significantly based on the chosen technology set. Furthermore they are notably influenced by production planning, heat exchanger surfaces and heat supply management. A reduction in energy intensity in the brewhouse processes will lead to the possibility to design heat supply equipment at lower capacity. The mashing process is an important candidate in considerations for heat recovery and low temperature heat supply. New temperature profiles in mashing can improve processing time, quality of the produced wort as well as enable the integration of low temperature heat in a better way.

1. Introduction

The European food industry is an important sector–15% of all employees working in producing companies are employed in the food industry (Food and Drink Europe, [34]). With increasing legislative pressure and consumer awareness the food industry is seeking solutions for a more sustainable production. Due to its long history, the food treatment and processing are very traditional processes. In many cases the technologies applied have not been changed over decades. As many of these technologies stem from a time prior to energy efficiency or renewable energy considerations, they often pose limitations when it comes to changing the energy supply. Traditionally most of the processes are steam driven and there is a number of challenges to overcome when low temperature energy (such as waste heat or renewable energy in form of solar heat) could be integrated. The widely applied stirred tank is one technology example that poses limitations to the integration of low temperature heat due to its low heat transfer coefficient and limited heat transfer area. Traditionally large temperature gradients are applied to overcome the limitations in heat transfer. To realise low temperature heat supply, however, retrofit changes are necessary to enable the required heat transfer rates.

There are many recommendations and manuals on how to improve energy efficiency in brewing, such as [1–3] or [4] and several case studies have been published recently, such as [5–10]. Energy consumption analysis based on production data acquisition systems and benchmarking have become state of the art in the brewing industry and dedicated tools are available [11]. The available material and the increasing environmental awareness in the sector have led to tremendous savings within the last decades [12,13]. However, as consumption figures vary widely (national data ranging between 70.6 and 243.1 MJ/hl [13]) there is still the continuing need for improvement, and often especially the last steps to reach a completely carbon-free production site are requiring detailed analysis. Recently approaches for monitoring and forecasting of energy consumption in brewing have been developed [14,15].

To reach an integrated sustainable production site, it is important to analyse effects of technology changes by considering the whole energy system of the production site. Process modelling is a decisive step in this evaluation: it allows a concise analysis of the status quo and enables parametric studies to reach an optimised technology set. Process modelling for energy efficiency optimisation can be done via EINSTEIN, a general thermal energy auditing tool for industry, which allows technology comparison to some extent [16,17]. Software tools, such as BATCHES, have also been applied for modelling and optimisation of brewhouses [18].

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Nomenclature

MJ/hl	thermal energy intensity (GJ/m^3)
$MEDT_{tech}$	minimal thermal energy demand per technology
$E_{mainmash[j]}$	energy demand in mash step j
$V_{mashing,mainmash[j]}$	volume of mash in mash step j
$roh_{mashing}$	density of mash
$cp_{mashing}$	specific heat capacity of mash
$T_{mashstep[j]}$	final temperature in mash step j
$T_{mashstep\_afterBMMix[j]}$	temperature in mash step j (after a boil-mash has been possibly added to the mash)
$j \ldots n$	indices for each mash step
m_{malt}	mass of malt
$m_{extract,ww}$	mass of extract in weak wort
$m_{weakwort,rec,mash}$	mass of weak wort which is recovered to the mash
$m_{spgrain}$	mass of spent grain
$p_{water\_spgrain}$	water content of spent grain
$T_{initial}$	initial temperature
$Q_{process}$	thermal power required for process heating
$m_{process}$	mass of process medium
$cp_{process}$	specific heat capacity of process medium
t_{start}	start time
t_{end}	end time
dTmin	minimal temperature difference required in heat exchange
HR	heat recovery

So far, there are no tools available dedicated for brewing which allow the analysis of energy efficiency opportunities based on detailed and holistic process modelling and parametric studies of operating conditions. The Green Brewery tool [17] was a start of this work with an Excel based tool for energy balancing of brewing sites. In this publication a "Brewery Model" is presented which allows analysing effects of different technologies on thermal energy demand in the brewing industry. For the mashing process an existing kinetic model has been applied to analyse the effects of new temperature profiles. These optimised temperature profiles will open the possibility to integrate low temperature energy. They have been validated at lab scale to show the potential of low temperature energy supply which is suggested for a process and technology change for the mashing process.

2. Methodology

A "Brewery Model" has been developed on EES (Engineering Equation Solver) to generate a holistic energy balance of a brewing facility. The calculation tool performs thermal energy demand calculations based on user-provided data. Further, time-variable energy demand per process as a basis for subsequent pinch analysis can be calculated. Visio flowsheets are used for visualisation of basic brewing flowsheets in EES where data can be entered. Various technologies can be chosen for mashing, boiling, wort cooling and packaging including different heat integration options (Table 1). Energy and mass balances are performed to calculate energy flows of each product stream. Results are presented in energy per hectolitre of brewed beer (for brewhouse and fermentation cellar) or packaged beer (for the packaging area). Parametric studies allow the comparison of different technology sets and/or production parameters. The model has been set up based on the experience of energy auditing in various international brewing sites and is thus applicable to various breweries with different site specifications.

2.1. Thermal energy demand modelling

The following equations show a calculation example of the mashing process. The energy demand is calculated per mash step in the time-temperature profile of the mashing process. One mash step is defined by two temperatures and the time required for the respective heating or holding.

$$E_{mainmash}[j] = V_{mashing,mainmash}[j] * roh_{mashing} * cp_{mashing} * (T_{mashsteps}[j] - T_{mashsteps\_afterBMMix}[j-1]) \quad (1)$$

with $T_{mashsteps}$ defining the temperature which is reached at the end of the current mashing step and $T_{mashsteps\_afterBMMix}$ taking into account whether a boil mash has been mixed to the main mash prior to this mash step. $V_{mashing,mainmash}$ gives the current mashing volume, again accounting for the possibility that a certain amount of mash is currently treated in a separate decoction mash.

Next to energy balances for single processes, overall mass and component balances are integrated to take into account the interdependences within the brewing process. An example is given below for the component balance of malt husks and extract:

$$m_{malt} + \frac{m_{extract,ww}}{m_{weakwort}} * m_{weakwort,rec,mash} = m_{extract} + m_{extract,ww} + m_{spgrain} * (1 - p_{water\_spgrain}) \quad (2)$$

As brewing is a batch process, thermal energy demand varies significantly over time. Therefore equations for calculating time-dependent energy demand were integrated for batch processes which are thermally relevant such as mashing, wort preheating, wort boiling, wort cooling and fermentation. Based on the existing (user-defined) energy supply and the given heat transfer area, the energy demand profile over time is calculated.

$$T = T_{initial} + \int \left(\frac{Q_{process}}{m_{process} * cp_{process}};\; t;\; t_{start};\; t_{end} \right) \quad (3)$$

The following flowsheet shows the overall calculation procedure for mashing; similar procedures have been developed for the other thermally relevant processes (Fig. 1).

2.2. Cooling demand modelling

For modelling the cooling demand the following processes are taken into account: brew water cooling, fermentation tanks, beer cooler, yeast tanks and maturation tanks (Fig. 2). The fermentation tanks are the largest consumers of cooling energy. Cooling demand of these tanks is therefore modelled over the biochemical equation of beer fermentation which can be stated in the following simplified way [19].

$$\text{maltose}(100\,g) + \text{aminoacids}(0.5\,g) \rightarrow \text{yeast}(5\,g) + \text{ethanol}(48.8\,g) + CO_2(46.8\,g) + \text{energy}(50\,kcal) \quad (4)$$

Of course a variety of other products, especially important for the beer flavour, are as well generated during fermentation, however they are less decisive when it comes to model the cooling requirement during fermentation. For modelling the cooling demand it is necessary to take into account the varying cooling rate which goes along with the fermentation rate of the beer. Therefore models from literature were evaluated to show the uptake of sugars and conversion to alcohol over time. The biochemical model proposed by Trelea et al. [33] can be used for the assessment of sugar consumption during the course of fermentation. It actually describes the production of CO_2 and relates it to sugar consumption, reduction of wort density and ethanol production. It also takes into account some effects of operating conditions, such as temperature and pressure. The model was built upon data taken from pilot