Contents lists available at ScienceDirect

Food and Bioproducts Processing

journal homepage: www.elsevier.com/locate/fbp

Multi-objective process optimisation of beer fermentation via dynamic simulation

*Alistair D. Rodman, Dimitrios I. Gerogiorgis**

Institute for Materials and Processes (IMP), School of Engineering, University of Edinburgh, The King's Buildings, Edinburgh EH9 3FB, United Kingdom

ARTICLE INFO

Article history:
Received 5 October 2015
Received in revised form 25 March 2016
Accepted 1 April 2016
Available online 13 April 2016

Keywords:
Beer
Fermentation
Flavour
Modelling
Simulation
Optimisation

ABSTRACT

Fermentation is an essential step in beer brewing: when yeast is added to hopped wort, sugars released from the grain during germination are fermented into ethanol and higher alcohols. To study, simulate and optimise the beer fermentation process, accurate models of the chemical system are required for dynamic simulation of key component concentrations. Since the entire beer production process is a highly complex series of chemical reactions with the presence of over 600 species, many of the specific interactions are not quantitatively understood, a comprehensive dynamic model is impractical.

This paper presents a computational implementation of a detailed model describing an industrial beer fermentation process, which is used to simulate published temperature manipulations and compare results with those obtained following the protocol currently in place at WEST Beer brewery (Glasgow, Scotland, UK). A trade-off between design objectives has been identified, making determination of a single optimal scenario challenging. A simulated annealing (SA) algorithm has been developed in order to pursue stochastic optimisation of the fermentor temperature manipulation profile, on the basis of generating an enormous set of plausible manipulations which adhere to suitable operability constraints at an appropriate level of temporal domain discretisation. The objective function considers ethanol maximisation as well as batch time minimisation (with variable weight allocation), and explicit constraints on diacetyl and ethyl acetate concentrations. Promising temperature manipulations have been determined, allowing for batch time reductions of as high as 15 h: this represents a substantial decrease in production cycle time, and is thus expected to improve annual plant throughput and profitability, without any discernible effect on flavour.

1. Introduction

1.1. *Fermentation*

The production of beer is well documented, with suggestions that it is one of the world's oldest prepared beverages, dating as early as the early Neolithic period (Arnold, 1911). Today beer is the most widely consumed alcoholic beverage in the world (Rehm et al., 2003) with the global beer market estimated to be over 500 billion USD in 2015 (Markets, 2013). The continual growth of the alcohol industry as a whole has resulted in an ever-increasing demand for beer products, with a rapid increase in the demand for super premium and craft beer products observed in the last five years. Market competitiveness makes it imperative that brewers operate their production processes effectively: the ability to improve any stage of production will have a significant effect on profitability and the ultimate success or failure of a brewery.

While many variations of the beer manufacturing process exist, industrial production almost invariably follows the scheme outlined in Fig. 1. Beer production is a complex chemical process: nevertheless, its only prerequisite is the use of the

* Corresponding author. Tel.: +44 131 651 7072.
E-mail address: D.Gerogiorgis@ed.ac.uk (D.I. Gerogiorgis).
http://dx.doi.org/10.1016/j.fbp.2016.04.002

Nomenclature

$()_0$	initial condition (–)
A_i	Arrhenius constant (species i) (K)
B_i	Arrhenius constant (species i) (K^{-1})
C_i	concentration (species i) ($g L^{-1}$)
X_{act}	active biomass concentration ($g L^{-1}$)
X_{dead}	dead biomass concentration ($g L^{-1}$)
X_{inc}	inoculated biomass concentration ($g L^{-1}$)
X_{lag}	latent biomass concentration ($g L^{-1}$)
X_{sus}	suspended biomass concentration ($g L^{-1}$)
Y_{EA}	ethyl acetate production stoichiometric factor ($g L^{-1}$)
k_e	ethanol affinity constant ($g L^{-1}$)
k_s	sugar affinity constant ($g L^{-1}$)
k_x	biomass affinity constant ($g L^{-1}$)
t_{lag}	length of fermentation lag phase (h)
μ_{AB}	diacetyl consumption rate ($g^{-1} h^{-1} L$)
μ_{DT}	specific cell death rate (h^{-1})
μ_{DY}	diacetyl growth rate ($g^{-1} h^{-1} L$)
μ_E	ethanol production rate (h^{-1})
μ_L	specific cell activation rate (h^{-1})
μ_S	sugar consumption rate (h^{-1})
μ_{SD}	specific dead cell settling rate (h^{-1})
μ_x	specific cell growth rate (h^{-1})
M	discrete time points (–)
N	discrete temperature points (–)
T	fermenter temperature (K)
f	fermentation inhibition factor ($g L^{-1}$)
t	time (h)
CO_2	carbon dioxide (–)
DY	diacetyl (–)
E	ethanol (–)
EA	ethyl acetate (–)
S	sugar (–)

same four essential ingredients: a starch source, yeast, hops and water (Southby, 1885).

Beer production requires few raw materials and many rudimentary processing techniques, however what is produced is a highly complex mixture of chemical species which govern product quality and flavour. It is the varying combinations of these compounds which are responsible for the unique taste of each beer brand, however many are unpleasant at certain concentrations. Diacetyl (2,3-butanedione) has a pungent butter-like aroma (Izquierdo-Ferrero et al., 1997), similar to banana flavouring agents (Hanke et al., 2010), and is often produced well above the flavour threshold in brewing. Due to their volatility, esters also contribute significantly to beer aroma; ethyl acetate is often used as an indicator of all esters present, and is described as having the odour of nail varnish remover. It is essential that efforts to improve fermentation efficacy are mindful of the degrading effect which these compounds have on product quality, if present in substantial quantity.

1.2. *Fermentation*

Fermentation is an essential brewing process unit operation, and the focus of this study. Yeast is introduced once the cooled wort (a sugar rich brewing intermediate, Hough et al., 1982) from the boiling process (Hudson and Birtwistle, 1966) enters fermentation vessels (*pitching*). The primary chemical reaction pathway is the conversion of sugar into ethanol and carbon dioxide, which is coupled with biomass growth and exothermic reaction heat generation. Concurrently, a wide range of species are formed at low concentrations by a multitude of side reactions, many of which contribute to beer flavour.

Fermentation progression is sensitive to yeast pitching rate (Guido et al., 2004), dissolved oxygen content, batch pressure and system temperature, which strongly affects yeast growth and metabolic rate: as long as yeast cells are not damaged and are kept below 30 °C, high temperature accelerates fermentation. Nevertheless, ethanol and volatile flavour component loss rates are too severe at higher temperatures, coupled with increased production of undesirable by-product compounds and bacterial growth promotion. Therefore, brewers control temperature inside the fermenter as the batch progresses, to accelerate fermentation while ensuring that yeast is not denatured and that no undesired by-product species are produced.

Online measurements can be cumbersome: each beer brand or line may have a proprietary temperature manipulation profile used for every batch, to ensure product consistency (Trelea et al., 2001). Offline measurements to assess fermentation progression are often limited to wort density or specific gravity. The Plato (specific gravity) scale represents equivalent sucrose concentration: sugar depletion is a useful indicator of the extent of fermentation. A primary concern of the brewing industry is the selection and implementation of an appropriate dynamic temperate profile throughout the fermentation process, to ensure high product quality, eliminate batch variations and ensure brand consistency and customer satisfaction.

Fermentation duration varies by product sought. Lagers are fermented at temperatures around 10 °C, requiring a fermentation time of about a week. Ales are fermented at higher temperatures (22 °C) and thus require 3–4 days (Boulton and Quain, 2008). Given the diversity of brewing operations around the world, many vessel types are used for fermentation. Typically, fermentation tanks are cylindro-conical stainless steel vessels. This shape promotes the circulation of CO_2 bubbles to agitate and mix the contents (which are not agitated or circulated by any mechanical means), helping to maintain a uniform vessel temperature. Moreover, it facilitates recovery of settled yeast from the cone, for lager-producing bottom yeasts. Conversely, ale-producing top yeasts settle at the free surface of the vessel and can be skimmed off. Fermentation tanks typically feature a cooling jacket, used to control the wort temperature in order to follow the brewer's desired profile. Larger tanks may include separate cooling mechanisms on the conical and cylindrical portions, allowing control of the internal circulation pattern (Boulton and Quain, 2008).

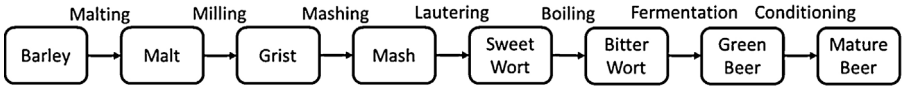

Fig. 1 – Block flow diagram of the beer production process.