Computers and Chemical Engineering 106 (2017) 582–595

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

Dynamic optimization of beer fermentation: Sensitivity analysis of attainable performance vs. product flavour constraints

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ARTICLE INFO

Article history:
Received 11 March 2017
Received in revised form 20 June 2017
Accepted 23 June 2017
Available online 29 June 2017

Keywords:
Beer fermentation
Dynamic optimization
Multi-objective optimization
Orthogonal collocation on finite elements
Sensitivity analysis
Flavour constraints

ABSTRACT

The declining alcohol industry in the UK and the concurrent surge in supply and variety of beer products has created extremely competitive environment for breweries, many of which are pursuing the benefits of process intensification and optimization. To gain insight into the brewing process, an investigation into the influence of by-product threshold levels on obtainable fermentation performance has been performed, by computing optimal operating temperature profiles for a range of constraint levels on by-product concentrations in the final product. The DynOpt software package has been used, converting the continuous control vector optimization problem into nonlinear programming (NLP) form via collocation on finite elements, which has then been solved with an interior point algorithm. This has been performed for increasing levels of time discretization, by means of a range of initializing solution profiles, for a wide spectrum of imposed by-product flavour constraints. Each by-product flavour threshold affects process performance in a unique way. Results indicate that the maximum allowable diacetyl concentration in the final product has very strong influence on batch duration, with lower limits requiring considerably longer batches. The maximum allowable ethyl acetate concentration is shown to dictate the attainable ethanol concentration, and lower limits adversely affect the desired high alcohol content in the final product.

1. Introduction

Determining how a modern industrial production process shall be operated typically involves mathematical optimization in some form. Often this will include an optimal control problem, where a system of state variables $[x]$ are influenced by an externally manipulatable control variable, u, so the optimal control vector $u(\mathrm{t})$ is sought to minimize an objective, φ, here considering only a terminal payoff (Biegler, 2010; Biegler et al., 2012):

$$\min_{u(t),t_f} \varphi\left(x\left(t_f\right), t_f\right) \tag{1}$$

$$\text{s.t}\ \frac{dx(t)}{dt} = f\left(x(t), u(t)\right),\ x(t_0) = x_0 \tag{2}$$

$$h\left(x(t), u(t)\right) = 0,\ g\left(x(t), u(t)\right) \le 0 \tag{3}$$

$$h_f\left(x\left(t_f\right)\right) = 0,\ g_f\left(x\left(t_f\right)\right) \le 0 \tag{4}$$

$$u(t)_L \le u(t) \le u(t)_U,\ x(t)_L \le x(t) \le x(t)_U \tag{5}$$

The ordinary differential equations (ODEs) which dictate the state trajectories (Eq. (2)) are influenced at any time by the current control (u) value, while Eq. (3) represents equality and inequality constraints across the entire time horizon, $t \in \left[t_0, t_f\right]$, with terminal constraints given by Eq. (4). Lastly, the state and control ranges are constrained within permissible bounds by Eq. (5).

An investigation into the beer manufacturing industry in the UK has been performed to determine if a strong incentive for process intensification and optimization exists. The alcohol industry as a whole has been in decline in recent years within the UK as shown in Fig. 1, where annual litres of pure alcohol per capita is the metric used to normalise for beverages of differing alcoholic strength. This is a result of several factors: people are drinking from a later age and regular drinkers are turning away from high strength products, towards more costly and lower strength drinks, such as craft beer.

Beer is however one of the few exceptions from the trend of a declining sector. The growing market share fuelled by recent increased demand for high value craft beer products produced on a small scale has led to the beer industry growing both in terms of production volume and market value. 1% year on year growth is

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http://dx.doi.org/10.1016/j.compchemeng.2017.06.024
0098-1354/

Nomenclature

Roman symbols

W_E	Objective ethanol weight (%)
W_t	Objective time weight (%)
X_A	Active biomass concentration ($g\,L^{-1}$)
X_D	Dead biomass concentration ($g\,L^{-1}$)
X_L	Latent 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 ($g\,L^{-1}$)
DY	Diacetyl (–)
EA	Ethyl acetate (–)
EtOH	Ethanol (–)
g	Inequality constraint (-)
h	Equality constraint (-)
K	Number of collocation points (-)
N	Number of elements in time horizon (-)
S	Sugar (–)
T	Fermenter temperature (K)
f	Fermentation inhibition factor ($g\,L^{-1}$)
t	Time (h)
t_f	Batch time (h)
u	Model control (-)
x	Model state (-)

Greek symbols

Δt_i	Length of element *i* (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})
Ω	State approximation polynomial (-)
φ	Objective function (–)
ψ	Control approximation polynomial (-)

Subscripts and operators

$\tilde{()}$	Normalised parameter (–)
$()_0$	Initial condition (–)
$()_L$	Lower bound (–)
$()_U$	Upper bound (–)
$()_i$	Property in element *i* (–)
$()_j$	Property at collocation point *j* (–)

predicted over the next 3 years, with the annual production volume in the UK expected to exceed 4.6 billion litres by 2019, compared to 4.2 billion in 2015. Fig. 2 shows the number of breweries in operation from 2010 to 2015 in the UK: it is evident that there is very steady increase which is predicted to continue moving forward.

Fig. 3 depicts the UK's alcohol consumption in context vs the rest of Europe. While Scots may have a reputation of being heavy drinkers, it is evident that while their per capita consumption is above the average for the rest of the UK, it is still a very typical value within Europe.

The declining alcohol industry and the surge in supply of beer products have created an extremely competitive environment for producers, many of whom must look towards process intensification if they are to remain profitable, forming the motivation for this study.

Within the beer production process, the fermentation stage is generally the system bottleneck, with batch times in excess of one week not uncommon. Fermentation progression depends on many variables (Rodman and Gerogiorgis, 2016b), however progression is dominated by the influence of the temperature of the involved substrates. As such, it is necessary to determine the temperature manipulation profile capable of Steering the process to completion in an optimal manner. High-resolution dynamic modeling, simulation and optimization (Akinlabi et al., 2007; Angelopoulos et al., 2013, 2014) are robust computational methodologies which can rigorously address the challenge of beer production acceleration without any discernible flavour and quality effects.

Approaches to process optimization fall under three areas (Bonvin, 1998):

- off-line optimization (open loop optimal control)
- run-to-run optimization
- on-line optimization

This study is concerned with the former: determining solutions to the off-line optimization problem to provide optimal open loop trajectories for the manipulated and state variables. These profiles are computed once, off-line, thus feedback elements are not included, and rather an ideal recipe for optimal production is produced. This approach is limited in terms of usefulness because in the presence of disturbances, these trajectories lose their optimal character (Canto et al., 2000), however on-line optimization is not practical: online concentration readings are extremely cumbersome to monitor in many cases. Rather many medium scale breweries elect to take a sample once the prescribed temperature trajectory has completed and determine the residual sugar content based on the product density (a surrogate measurement for total sugar content) via the Plato scale, to confirm if the batch has completed fermentation as expected and desired. This convention renders any attempt to incorporate an online control loop for control of state (concentration) trajectory control non-applicable to this particular problem and is the reason why our study is focused on off-line optimization. A beer brand or line instead typically has a proprietary temperature manipulation profile (recipe) used for every batch, to ensure product consistency, which fits the scope of this work.

2. Process description

2.1. Beer fermentation

Fermentation is an essential step in the manufacture of alcoholic beverages, responsible for the characteristic taste of the final product and its alcohol content (Rodman and Gerogiorgis, 2016c). Upstream processing produces a sugar rich intermediate (wort) from a feedstock starch source (most typically malted barley). Once cooled to an appropriate initial temperature, the wort enters stainless steel vessels along with yeast, allowing fermentation to commence. The primary chemical reaction pathway is the conversion of sugars into ethanol and carbon dioxide, which is coupled with biomass (yeast) growth and heat generation from the exothermic reaction. Concurrently, a range of species are formed at low concentrations by a multitude of side reactions, many of which may impact product flavour above threshold concentrations. Fermentation is completed once all consumable sugars have been converted by the yeast into alcohol, following which the solution leaves the fermenter for subsequent downstream processing prior to sale and consumption.