MODELING AND SIMULATION OF THE BEER FERMENTATION PROCESS AND TEMPERATURE CONTROL

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Thesis submitted in partial fulfillment of the requirements for the degree Master of Science in Sustainable Process Development

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Dedication

I dedicate this thesis for my parents and teachers, who have supported me all the way since the beginning of my studies.

Also, this thesis is dedicated to my fiancée who has been a great source of motivation and inspiration.
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First and foremost, I am heartily thankful to my supervisor, Professor Bernt Lie, Telemark University College, Norway, for the valuable guidance and advice from the initial to the final level, enabled me to develop and understanding of the subject. This thesis would not have been possible unless my supervisor’s great contribution. I also would like to thank him for arranging a scholarship to get an exposure in Norway with valuable experience and knowledge.

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Abstract

Beer is the most common alcoholic drink around the world. When talking about the beer quality, flavor of the beer is more concerned. Most of the brewers in Sri Lanka are using traditional methods to brewing beer. Most of brewers using pre identified recipe to produce mass production of beer. Therefore, beer quality i.e. flavor is varying brand by brand. It is important to study the variation of temperature, how will affect to the final alcohol production and the flavor compound formation. Beer manufacturing industry can be used this knowledge to increase the production efficiency and the product quality.

It is very important to know about dynamics of forming flavor compounds. In this work the fermentation process is concerned since all the flavor compounds are formed during the fermentation. The mechanistic model is developed by based on the knowledge of biochemical processes in the yeast cell and previously developed mathematical models which are available in the literature. There are many beer models can be found such as Engasser et al.,(1981); Growth kinetic model, Gee at al.,(1988), Phisalaphong et al.(2006); Growth kinetic model and effect on temperature, W.F. Ramirez and J. Maciejowski.,(2007); Optimal beer fermentation, etc. The beer fermentation process is modeled and simulated in MATLAB/Simulink environment.

Growth model, nutrient model, and the flavor model are considered and developed. Growth model consists of sugar consumption, biomass growth and ethanol formation models. Those models are developed with temperature dependent parameters to observe the effect of the temperature. Three amino acids which are valine, leucine and iso leucine are considered for the Nutrient model. Consumption of these three amino acids is considered during fermentation. Flavor model is developed based on the growth model and the nutrient model. Flavor compounds are categorized into three groups which are fusel alcohols, esters and vicinal diketones. Altogether nine parameters are considered as flavor compounds and the effects of temperature on those are simulated with MATLAB/Simulink and JModelica. Industrial temperature profile is obtained and applied for the developed model and simulated in MATLAB/Simulink and the results are analyzed.

PI controller is applied to get identified temperature profile to obtain flavor formation and the dynamic model is used for find suitable controller parameters for the best control. The controller is simulated in MATLAB/Simulink.

Keywords: Beer, Fermentation, Flavor, Modeling, Simulation, Temperature, Control
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## Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>Glucose concentration (mol/m³)</td>
</tr>
<tr>
<td>M</td>
<td>Maltose concentration (mol/m³)</td>
</tr>
<tr>
<td>N</td>
<td>Maltotriose concentration (mol/m³)</td>
</tr>
<tr>
<td>X</td>
<td>Biomass concentration (mol/m³)</td>
</tr>
<tr>
<td>E</td>
<td>Ethanol concentration (mol/m³)</td>
</tr>
<tr>
<td>µ₁</td>
<td>Specific rate of glucose uptake (h⁻¹)</td>
</tr>
<tr>
<td>µ₂</td>
<td>Specific rate of maltose uptake (h⁻¹)</td>
</tr>
<tr>
<td>µ₃</td>
<td>Specific rate of maltotriose uptake (h⁻¹)</td>
</tr>
<tr>
<td>µₓ</td>
<td>Specific rate of yeast growth (h⁻¹)</td>
</tr>
<tr>
<td>YₓG</td>
<td>Yield coefficient, mole X per Mole G</td>
</tr>
<tr>
<td>YₓM</td>
<td>Yield coefficient, mole X per Mole M</td>
</tr>
<tr>
<td>YₓN</td>
<td>Yield coefficient, mole X per Mole N</td>
</tr>
<tr>
<td>x₀</td>
<td>Initial yeast concentration (mol/m³)</td>
</tr>
<tr>
<td>YₓEG</td>
<td>Yield coefficient, mole E per Mole G</td>
</tr>
<tr>
<td>YₓEM</td>
<td>Yield coefficient, mole E per Mole M</td>
</tr>
<tr>
<td>YₓEN</td>
<td>Yield coefficient, mole E per Mole N</td>
</tr>
<tr>
<td>kₓ</td>
<td>Empirical yeast growth inhibition constant (mol/m³)²</td>
</tr>
<tr>
<td>µᵢ</td>
<td>Maximum reaction velocity for iᵗʰ sugar (i = G, M or N, h⁻¹)</td>
</tr>
<tr>
<td>Kᵢ</td>
<td>Michaelis constant for iᵗʰ sugar (i = G, M or N, mol/m³)</td>
</tr>
<tr>
<td>Kᵢ’</td>
<td>Inhibition constant for iᵗʰ sugar (i = G or M, mol/m³)</td>
</tr>
<tr>
<td>µᵢ₀</td>
<td>Arrhenius frequency factor for maximum velocity (h⁻¹)</td>
</tr>
<tr>
<td>Kᵢ₀</td>
<td>Arrhenius frequency factor for michaelis constant (mol/m³)</td>
</tr>
<tr>
<td>Kᵢ₀’</td>
<td>Arrhenius frequency factor for inhibition constant (mol/m³)</td>
</tr>
<tr>
<td>Eᵢµ</td>
<td>Arrhenius activation energy for maximum velocity (cal/mol)</td>
</tr>
<tr>
<td>EᵢKi</td>
<td>Arrhenius activation energy for michaelis constant (cal/mol)</td>
</tr>
<tr>
<td>Eᵢµᵢ</td>
<td>Arrhenius activation energy for inhibition constant (cal/mol)</td>
</tr>
</tbody>
</table>
R  Gas constant (cal/mol K)
T  Temperature (°C)
ρ  Density of wort (kg/m3)
Cp  Specific heat capacity of wort (kg/mol °K)
ΔH_{FG}  Overall heat of formation for glucose (J/mol)
ΔH_{FM}  Overall heat of formation for moltose (J/mol)
ΔH_{FN}  Overall heat of formation for molotrise (J/mol)
Y_{LX}  Yield coefficient, moles leucine needs per mol biomass growth
Y_{IX}  Yield coefficient, moles isoleucine needs per mol biomass growth
Y_{VX}  Yield coefficient, moles valine needs per mol biomass growth
K_L  Michaelis constant for leucine (mol/m3)
K_I  Michaelis constant for isoleucine (mol/m3)
K_V  Michaelis constant for valine (mol/m3)
L  leucine concentration (mol/m3)
I  Isoleucine concentration (mol/m3)
V  Valine concentration (mol/m3)
D  First order time delay (h)
τ_d  First order time constant for delay (h)
t  Time (h)
IB  Isobutyl alcohol concentration (mol/m3)
IA  Isoamyl alcohol concentration (mol/m3)
MB  2-methyl-1-butanol concentration (mol/m3)
P  n-propanol concentration (mol/m3)
Y_{IB}  Isobutyl alcohol yield
Y_{IA}  Isoamyl alcohol yield
Y_{MB}  2-methyl-1-butanol alcohol yield
Y_{PE}  n-propanol alcohol yield
μ_V  Specific rate of valine uptake (h⁻¹)
μ_L  Specific rate of leucine uptake (h⁻¹)
μ_I  Specific rate of isoleucine uptake (h⁻¹)
EA  Ethyl acetate concentration (mol/m3)
EC  Ethyl caproate concentration (mol/m3)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAc</td>
<td>Isoamyl acetate concentration (mol/m³)</td>
</tr>
<tr>
<td>Y_{EA}</td>
<td>Ethyl acetate yield per mole sugar fermented (mol/m³)</td>
</tr>
<tr>
<td>Y_{EC}</td>
<td>Yield coefficient for ethyl caproate per mole bio mass growth (mol/m³)</td>
</tr>
<tr>
<td>Y_{IAc}</td>
<td>Yield coefficient for moles isoamyl acetate produced per mole isoamyl alcohol formed (mol/m³)</td>
</tr>
<tr>
<td>µ_{IA}</td>
<td>Specific rate of isoamyl alcohol formation (h⁻¹)</td>
</tr>
<tr>
<td>VDK</td>
<td>Vicinal diketones concentration (mol/m³)</td>
</tr>
<tr>
<td>Y_{VDK}</td>
<td>Yield coefficient, mole VDK formed per mol biomass growth</td>
</tr>
<tr>
<td>K_{VDK}</td>
<td>Effective first order rate constant for uptake of VDK (m³/mol h)</td>
</tr>
<tr>
<td>AAl</td>
<td>Acetaldehyde concentration (mol/m³)</td>
</tr>
<tr>
<td>Y_{AAl}</td>
<td>Yield coefficient, moles AAl formed per mole sugar fermented</td>
</tr>
<tr>
<td>K_{AAl}</td>
<td>Effective first order rate constant for uptake of AAl (m³/mol h)</td>
</tr>
<tr>
<td>Ke</td>
<td>Controller gain</td>
</tr>
<tr>
<td>τ_i</td>
<td>Integral time (h)</td>
</tr>
<tr>
<td>SP</td>
<td>Set point</td>
</tr>
<tr>
<td>GS</td>
<td>Observed parameter for gain scheduling</td>
</tr>
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</table>