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Dynamic Heat Transfer modeling, and Simulation of Biomass Fermentation during Beer Processing

Bayisa Dame Tesema[1], Solomon Workneh[2], Carlos Omar[3]

[1]Chemical Engineering Department, Adama Science and Technology University, Adama, Ethiopia
[2]Chemical Engineering Department, Bahir Dar University, Bahir Dar, Ethiopia
[3]Department of Agricultural Economics, Mexico

ABSTRACT

The study focuses on the modeling of the temperature profile during the fermentation of beer and the selection of the modelled temperature to simulate the growth of a microorganism, the consumption of proteins and the formation of aromatic compounds (ketone and esters). The objective of the study was to determine how to select the best temperature for beer fermentation and how a portion of the biochemical reaction occurs with the controlled (selected) temperature. Finite element modelling has been used for heat transfer modelling and COMSOL Multiphysics version 5.3 has been used for implementation. Version 17 of MATLAB was used to simulate biochemical changes with the chosen temperature. The simulated results showed that at high coolant flow, a low-temperature profile was recorded over the fermentation time. As such, the observed temperatures were 1.2m3/hr, 1.3m3/hr and 1.6m3/h, 20 oC, 18 oC and 12.5 oC, respectively. The modelled vorticity results also indicated that at a flow rate of 1.2m3/hr, there was a consistent flow of liquid around the agitation center relative to other coolant flows. Isoleucine was exhausted after 13hr at 12.5°C, 80hr at 18°C and 16hr at 20°C from the start of fermentation. The simulated results also indicated that ethyl acetate had reached a hold-back value of 0.114mol/m3 at 70hr at 12.5oC, 30hr at 18oC, and 22hr at 20oC. However, isoamyl acetate retained a retention value of 0.0105 mol/m3 until the initial concentration of sugar and amino acids was exhausted (throughout fermentation) at all selected temperatures. Valine decreased to nearly 195hr at 12.5°C, 120hr at 18°C and 85hr at 20°C. The simulated nutrient results were again shown to be zero in 210hr at 12.5°C, 110hr at 18°C and 90hr at 20°C of luicine consumption.

KEYWORD: *Fermentation, Flavor, Modelling, Temperature*

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1. INTRODUCTION

Fermentation produces energy from the oxidation of organic compounds. In the case of beer, fermentation is an important process unit operation. The initial chemical reaction pathway is the conversion of sugar into ethanol and carbon dioxide molecule, coupled with exothermic reaction and heat and biomass growth (MacDonald et al., 2008). Concurrently, a number of organic compounds (many of which contribute to or compromise beer flavor) are formed at low concentrations, due to the multitude of side reactions.

Beer fermentation is one of the large-volume industrial processes that are essentially controlled manually. There are several reasons that excluded automation from this process so far. One is that the essential process state variables are difficult to measure on-line. Another is that the fermentation process appears to be a complex system, which had not been modeled precisely enough so far. On the other hand, however, the brew masters make excellent beers with their current technology and any automatic process supervision and control system must compete with these highly skilled human controllers (Sablayrolles JM and Ball CB, 2004). Automatic systems would only be of interest to breweries if they would help the brew masters to produce the same quality of beer in a much less expensive way. There are some obvious entry points for further auto-mat ion in beer fermentation. In beer breweries, many tasks presently being performed by men as well as women, such as manual cleaning, filling, pitching, measuring, temperature control, yeast harvesting, pumping into lager vessels, etc., could be automated (Gaurdia, 2001).

The fermentation of alcohol is the most time-consuming step in brewing. It can take up to two weeks to complete. Fermentation progression is sensitive to yeast pitching rate, dissolved oxygen content, batch pressure and temperature. The system temperature strongly affects yeast growth and metabolic rate: as long as yeast cells are kept below 30ºC and not damaged, higher temperatures accelerate fermentation (Skye&Ling, 2012). Beyond this temperature, ethanol and volatile flavor compound loss rates are too severe, coupled with increased production of undesirable substances and bacterial growth. Brewers control ferment or temperature within a narrow range during batch progression, to accelerate the fermentation

while also ensuring that yeast is not deactivated due to denaturation and that no undesirable flavor compounds are produced.

2. Model governing equations and description

Diffusion and reaction of temperature flow in the beer fermentation tank is integrated to an ordinary differential equation as written below. It can be solved by finite element method. The finite element method is a numerical approach by which general differential equations can be solved in an approximate manner. The differential equation or equations, which describe the physical problem considered, are assumed to hold over a certain region. This region may be one-, two- or three-dimensional. It is a characteristic feature of the finite element method that instead of seeking approximations that hold directly over the entire region, the region is divided into smaller parts, so-called finite elements, and approximation are then carried out each element. The collection of all elements is called a finite element mesh. When the type of approximation which is to be applied over each element has been selected, the corresponding behavior of each element can then be determined. This can be performed because the approximation made over each element is fairly simple.

During beer fermentation conduction-convection mode of heat transfer occurs from between beer film and bulk beer, between bulk beer and the coolant. Equations which govern this heat transfer are described as follows. In beer fermentations the governing equation for flow of heat between medium and the growing yeast is derived from the energy balance as follows. The basic assumption of the model governing equation are;

- Cooling jacket is well insulated. No heat loss to the surrounding.
- Specific heat capacity of the wort and the coolant remains unchanged over entire fermentation time.
- Density of wort and the coolant remains unchanged over entire fermentation time
- Assume wort is homogeneous liquid.
- Assume the flow is laminar

Energy balance for fermentation tank

Rate of energy accumulated = rate of energy in- rate energy of out + rate of energy generated– rate of energy lost.

$\frac{dE}{dt} = 0 - 0 + E_{gen} - Q$, no rate of energy in and out.

$Q = \mathrm{U} * \mathrm{A} * \Delta T_{lm}$,

Hence

$d(mC_pT)/dt = -X(\Delta H_{FG} * \mu_1) * V - U * A * \Delta T_{lm}$, where $\Delta T_{lm} = T - T_j / \ln T/T_j$

$m = \rho V$

$d(\rho * V * Cp * T)/dt = -X * \Delta H_{FG} * \mu_1 * V - U * A * \Delta T_{lm}$

$dT/dt = -X * \Delta H_{FG} * \mu_1 / \rho * C_p - U * A * \Delta T_{lm} / \rho * C_p * V$ (1)

Energy balance for cooling jacket

Following the same procedure from which is energy balance on cooling jacket; $Rateofenergyacumulated = Rateofenergyin - Rateofenergyout + Rateofenergygenerated - Rateofenergylost$

$\frac{dE}{dt} = E_{in} - E_{out} + 0 + Q$

$d(m_j * C_{pc} * dT_j)/dt = \rho_c * F_c * C_{pc} * T_c - \rho_c * F_c * C_{pc} * T_j + U * A * \Delta T_{lm}$

$m = \rho_c * V_j$

Hence

$dT/dt = \rho_c * F_c * C_{pc} * T_c / \rho_c * V_j * C_{pc} - \rho_c * F_c * C_{pc} * T_j / \rho_c * V_j * C_{pc} + U * A * \Delta T_{lm}$

$dT/dt = F_c (T_c - T_j)/V_j + U * A * \Delta T_{lm} / \rho_c * V_j * C_{pc}$(2)

The governing equation for heat flow between film beer and the wall is the conduction-convention heat transfer which is;

$\rho C_p \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y}\right) = k(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial^2 y})$, in vector form as follows;

$dz * \rho * C_p \frac{\partial T}{\partial t} + dz * \rho * C_p * \boldsymbol{u}.\boldsymbol{\nabla T} + \boldsymbol{\nabla}.\boldsymbol{q} = dzQ + q_o + dzQ_p + dzQ_v$(3)

For laminar flow the incompressible Naiver stokes equation and continuity equation is used.

$\rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right), xmomentumequation$

$\rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \rho g \beta (T - Tref), ymomentumequation$

In vector form the two-equation combined as follows.

$\frac{\rho \partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u}.\nabla)\boldsymbol{u} = \nabla[-\rho \boldsymbol{I} + \mu(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T)] + F$(4)

$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}, contuinityequation$, but in vector form

$\rho \nabla.(\boldsymbol{u}) = 0$ (5)

For transport of diluted species;

$\frac{\partial Ci}{\partial t} + \nabla.(-Di \nabla Ci) + \boldsymbol{u}.\nabla Ci = Ri$(6)

$\boldsymbol{Ni} = -Di \nabla Ci + \boldsymbol{u} Ci$

2.1. Model geometry

Most of the beer processing industry uses cylindroconical shape of fermentation tanks. Therefore, the selected geometry was 2D axial symmetry of cylindro - conical shape with mixing direction and flow direction from upper to lower as shown in figure 2.1.

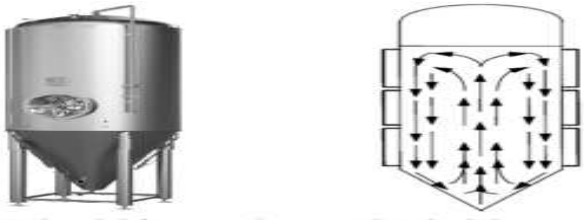

Figure 2.1 Model geometry for finite element modeling (Yusuf and Muray Moo, 2003).

2.2. Nutrient consumption kinetics model (Warnasooriya, 2011)

Formation of some of flavor compound such as fusel alcohols have related to consumption of certain amino acids. These amino acids are utilized by the cell primary as structural components in the construction of structural and functional proteins. The rate of amino acids

assimilation by yeast is therefore modeled as negatively proportional to the yeast growth rate and this is limited by availability of amino acids in the media.

Luicine consumption rate

$$\frac{dL}{dt} = -Y_{LX} * \frac{dX}{dt} * \frac{L}{K_L + L} * D \quad (7)$$

Where Y_{LX} = Yield coefficient moles luicine need per mole biomass growth, K_L = Michaels constant for luicine (mol/m^3), L = Luicine (mol/m^3), D = First order time delay (Michiko et al.).

Isoluicine consumption kinetics rate

$$\frac{dI}{dt} = -Y_{IX} * \frac{dX}{dt} * \frac{I}{+I} * D \quad (8)$$

Where Y_{IX} = Yield coefficient of isoluicine needed per mole biomass growth, K_I = Michaels constant for isoluicine (mol/m^3), D = First order time delay (Michiko et al.).

Valine consumption kinetics rate

$$\frac{dV}{dt} = -Y_{VX} * \frac{dX}{dt} * \frac{V}{K_V + V} * D \quad (9)$$

Where Y_{VX} = Yield coefficient of Valine needed per mole biomass growth, K_V = Michaels constant for valine (mol/m^3), V = valine (mol/m^3).

In all cases first order time delay is represented by:

$$D = 1 - e^{-t/\tau d}$$

Yeast growth kinetics

$$\frac{dX}{dt} = \mu_x * X \quad (10)$$

Where

$\mu_x = (Y_{XG} * \mu_1 + Y_{XM} * \mu_2 + Y_{XN} * \mu_3) * \frac{Kx}{Kx + (x - xo)2}$, is the specific rate of yeast growth.

$\frac{Kx}{Kx+(x-xo)^2}$ = is the indication of cell growth inhibition of unsaturated fat.

Where Y_{XG} = Yield coefficient mole X per mole G, Y_{XM} = Yield coefficient mole X per mole M, Y_{XN} = Yield coefficient mole X per mole N, Kx = Empirical yeast growth inhibition constant (mol/m^3)^2, X_o = initial yeast concentration (mol/m^3)

Esters model(Warnasooriya, 2011)

The synthesis of aroma active esters by yeast is of great importance because they represent the largest group of flavor active compound in beer (ethyl acetate, isoamyl acetate, ethyl caproate and etc.).

Ethyl acetate formation kinetics

$$\frac{dEA}{dt} = Y_{EA} * (\mu_1 + \mu_2 + \mu_3) * X \quad (11)$$

Where Y_{EA} = Ethyl acetate yield per mole sugar fermented Where $\mu 1 = \frac{\mu G * G}{KG + G}$, Where μ_G = Specific uptake of glucose (h^{-1}), K_G = Consumption rate constant of glucose (Mol/m^3), G = glucose (Mol/m^3),$\mu 2 = \frac{\mu M * M}{KM + M} * \frac{KG'}{KG' + G'}$Where μ_M = Specific uptake of maltose (h^{-1}), M = maltose (Mol/m^3), K_M = Consumption rate constant of maltose (Mol/m^3), K'_G = Consumption rate constant of glucose (Mol/m^3), G' = glucose (Mol/m^3).$\mu 3 = \frac{\mu N * N}{KN + N} * \frac{KG'}{KG' + G} * \frac{KM'}{KM' + M}$Where μ_N = Specific uptake of malt trios (h^{-1}), N = Concentration of malt trios (Mol/m^3), K'_M = Consumption rate constant of maltose (Mol/m^3).

Ethyl caproate formation kinetics.

$$\frac{dEC}{dt} = Y_{EC} * \mu_x * X (12)$$

Where Y_{EC} = Yield coefficient for ethyl caproate per mole biomass growth, μx = specific rate of yeast growth (h^{-1}).

Isoamyl acetate formation kinetics.

$$\frac{dIAc}{dt} = Y_{IAc} * \mu_{IAc} * X (13)$$

Where Y_{IAc} = Yield coefficient for mole Isoamyl acetate produced per mole Isoamyl alcohol formed, IAc = Isoamyl acetate concentration (Mol/m^3).

3. RESULT AND DISCUSION.

3.1. Effect of coolant flow rate on fermentation temperature and flow condition.

The temperature profile, flow conditions and vorticity of flow have been discussed in this section at a different coolant flow rate. From the modeled results, the temperature profile of beer fermentation was observing with fermentation time (Fig.3.1, 3.2 &3. 3). Again, velocity streamlines has been also solving from naiver stokes equation to see flow condition with a time of fermentation.

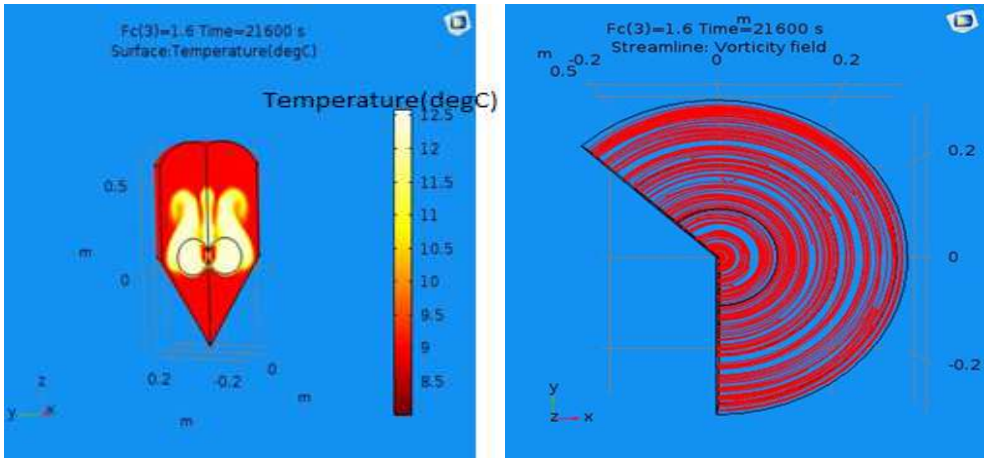

Figure 3.1 Temperature profile (inner), and vorticity field at 1.6 m^3/hr coolant flow rate

The results also included vorticity field with fermentation time from naiver stokes equation to see the formation of the vortex at a different coolant flow rate. During beer fermentation, the temperature of fermentation is controlled by liquid circulated ammonia (Anderson, 2006). Vortex formation during fermentation controls mass transfer and the rate of dissolved oxygen (Rubenberger, 2006). This liquid ammonia is controlled by its flow rate. The model was tried to relate the coolant flow rate to temperature profile from an energy balance (eqn 1and 2 above).

The modeled results were indicating that all phenomena of beer fermentation like air flow (oxygen consumption), temperature profile with time, padic pressure with fermentation time and formation of the vortex have influenced by the coolant flow rate (Fig.3.1, 3.2 and 3.3). The results indicated that the increasing coolant flow rate decrease temperature profile within the fermentation tank (Fig.3.1, 3.2 and 3.3).This indicates that the increasing coolant flow rate increases the heat exchange area, hence the high amount of heat absorbed or removed from the coolant from the tank which produced exothermically as sugar decomposes to ethanol and carbon dioxide with fermentation time.

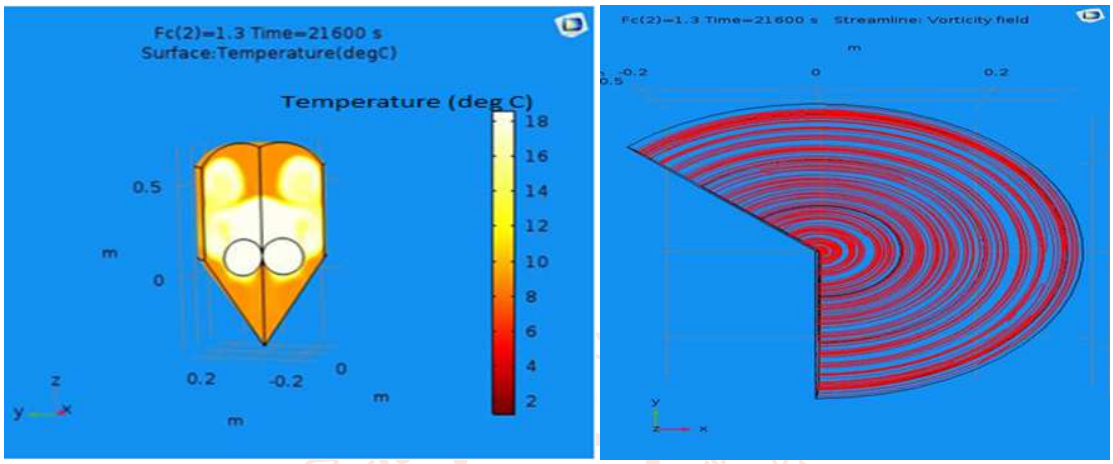

Figure 3.2 Temperature profile (inner), and vorticity field at 1.3m^3/hr coolant flow rate.

The velocity streamline was indicating that the flow condition of the fermentation was from bottom to top (upside down) at all coolant flow rates and also possible to judge the uniformity of flow at these coolant flowrate, which is better at 1.2 m^3/hr and slightly uniformity decreased for the rest offlow rate (Fig.3.1, 3.2 and 3.3). This indicated that as the coolant flow rate increased, the temperature profile within the fermentation tank cannot form uniform mixing which is not favorable for mass transfer rate.

The modeled vorticity results were also indicating that at 1.2 m^3/hr coolant flowrate, uniform flow of fluid was observed around the stirring center than other coolant rates, which is responsible for a high transfer rate of dissolved oxygen (Fig.3.1, 3.2 and 3.3).

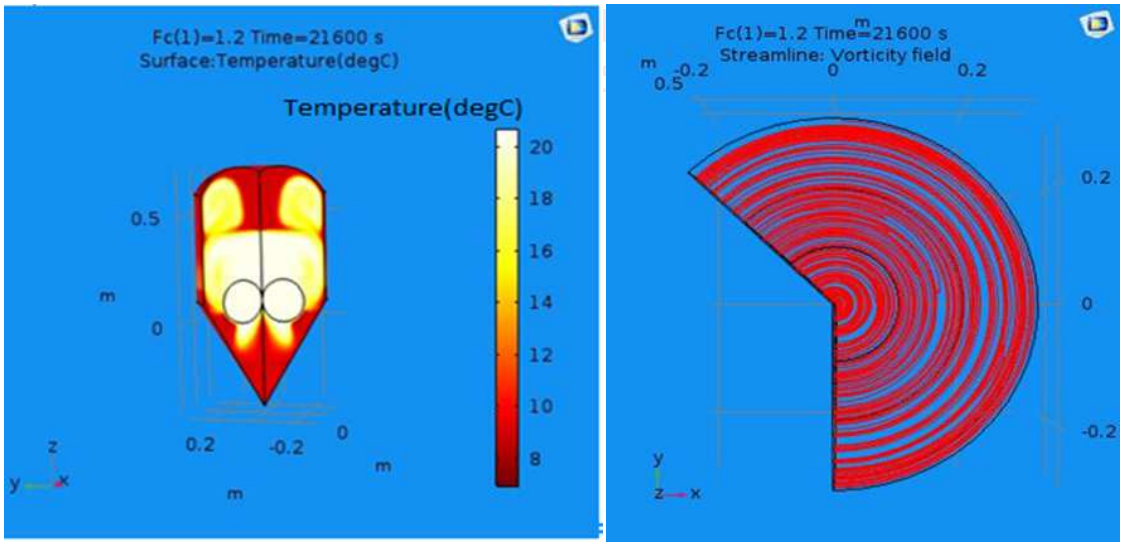

Figure 3.3 Temperature profile (inner), and vorticity field at 1.2 coolant flow rate

3.2. Effect of temperature on fermentation time and beer flavor quality

The biochemical reaction has been simulating at a different temperature, which already modeled at a different coolant flow rate by the finite element method.

3.2.1. Effect of temperature on nutrient consumption rate.

Isoluicine was depleted after 130 hours at 12.5^{o}C, 80 hrs at 18^{o}C and 16 hrs at 20^{o}C from the start of fermentation time (Fig 3.4, 3.5 and 3.6). The time of consumption at 18 ^{o}C and 20^{o}C was decreased by 10 hrs and 30 hrs than at 16 ^{o}C (current

company value) temperatures respectively. Valine was keeping, decreasing until almost 195 hrs at 12.5°C, 120 hrs at 18°C and 85 hrs at 20°C (Fig 3.4, 3.5 and 3.6).

The amount of Valine in the initial concentration of wort must keep to low concentration (J. R. Dickinson et al., 2003) to maintain higher alcohol production to below thresh hold value. Since the growth of yeast was still maintained after depletion of Valine to zero concentration, Valine concentration was counting negative concentration until both maltose and malt trios became a zero concentration (Fig 3.4, 3.5 and Fig 3.6). This indicated that the initial concentration of Valine is not enough to consume all maltose and malt trios.

The simulated results of the nutrient were again indicating that the given initial nutrient was become zero after 210 hrs at 12.5°C, 110 hrs at 18°C and 90 hrs at 20°C for luicine consumption (Fig.3.4, 3.5 and 3.6). These times of consumption were indicating that decreasing fermentation temperature increase consumption time of leucine as well as isoleucine.

3.2.2. Effect of temperature on rate of esters produced.

The simulated result of esters was indicating that the amount of ethyl acetate formed by fermentation time is relatively higher than ethyl caproate and isoamyl acetate in mole per cubic meter (Fig. 3.7, 3.8 and 3.9). Higher alcohols and esters are desirable volatile beer constituents, with a few exceptions (Hanke, 2010). Only isoamyl acetate (banana-like aroma) concentration is usually above the threshold level in most lager beers, ales normally have ethyl acetate (solvent-like aroma) and ethyl hexanoate (apple-like aroma) as supplementary flavoring compounds with levels above their threshold taste. Ethyl acetate is the most common ester produced by yeast (Hanke, 2010).

Several by-products of amino acid metabolism in yeast yield (produce) different flavors in the beer. These flavor-active esters are formed by the condensation reaction between either acetyl/Acyl-CoA and higher alcohols or ethanol (Warnasoriya, 2010). The final concentrations of higher alcohols and ethyl ester or acetate ester derivatives are therefore dependent on the uptake efficiency of the corresponding amino acid and the sugar utilization rate. The simulated results were also indicating that ethyl acetate formation follows consumption of Valine amino acids and maltose sugar (Fig.3.6, 3.7&3.8).

From the simulated result, ethyl acetate was reachingit's thresh hold value of 0.114 Mol/m^3 after 70 hrs at 12.5°C hours, 30 hrs at 18°C and 22 hrs at 20°C. But, isoamyl acetate maintained thresh hold value of 0.0105 Mol/m^3 (Engan, 2008) until the initial concentration of sugar and amino acid were depleted (throughout fermentation time). This indicated that unless ethyl ester, isoamyl ester has no flavor effect on the specified condition.

The simulated results were indicating that esters-based flavor active compounds were obtained at an early stage of fermentation time at the specified condition which agrees with actual beer fermentation (Fiqadu, 2012).Atthe fermentation time increased the production rate of ethyl acetate and ethyl caproate was increasing at a decreasing rate. This decreasing rate has come from depletion of the initial concentration of both glucose and nutrient.

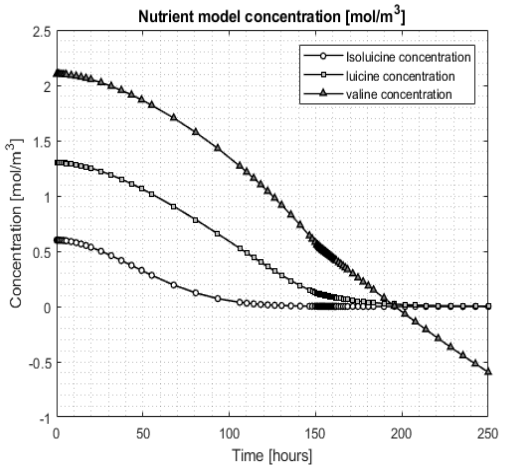

Figure 3.4Simulated result of nutrient model concentration at the temperature 12.5 °C, 50 Mol/m^3 pitching rate and 1.3 Mol/m^3, 0.6 Mol/m^3 and 2.1 Mol/m^3 concentration (initial) for luicine, isoluicine and Valine respectively.

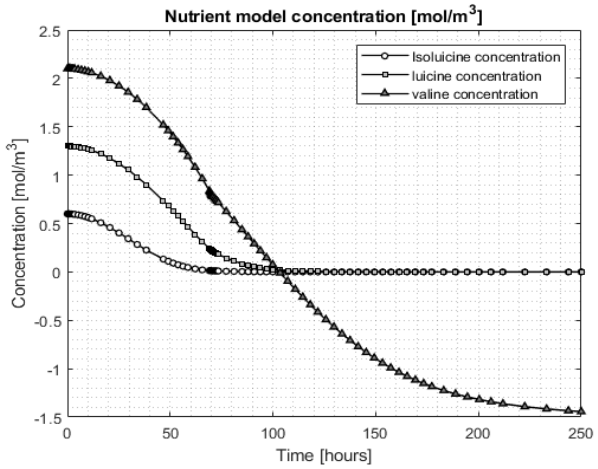

Figure 3.5 Simulated result of nutrient model concentration at temperature 18°C, 50 Mol/m^3 pitching rate and 1.3 Mol/m^3, 0.6 Mol/m^3 and 2.1 Mol/m^3 concentration for isoluicine, luicine and Valine respectively.

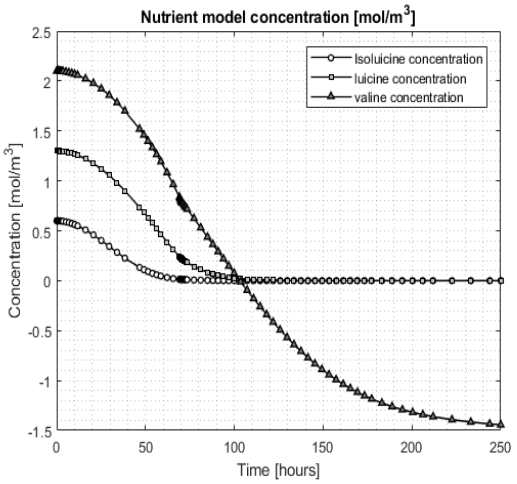

Figure 3.6Simulated result of nutrient model concentration at temperature 20°C, 50 Mol/m³ pitching rate and 1.3 Mol/m³, 0.6 Mol/m³ and 2.1 Mol/m³ concentration (initial) for isoluicine, luicine and Valine respectively.

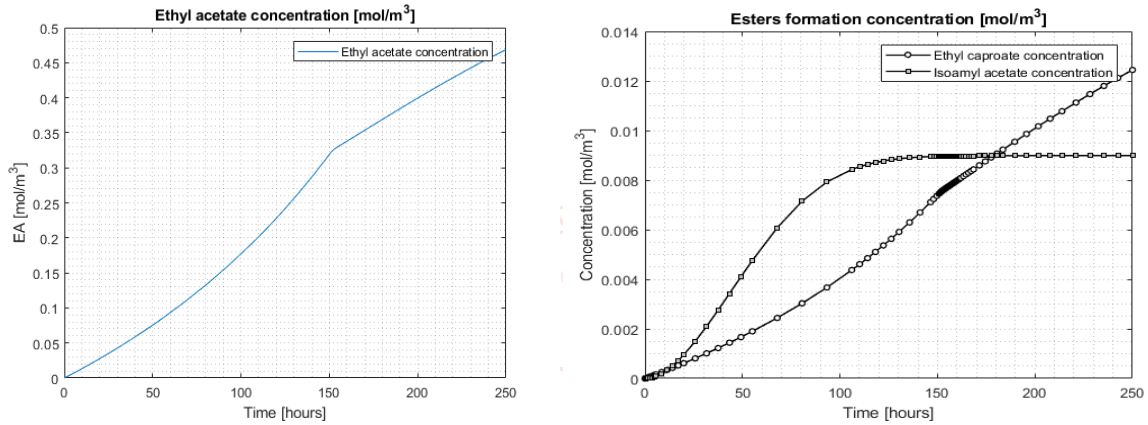

Figure 3.7 Esters model simulated result at temperature 12.5 °C, pitching rate 50 Mol/m³ and 200 Mol/m³, 320 Mol/m³ and 100 Mol/m³ concentration (initial) for glucose, maltose and malt triose respectively.

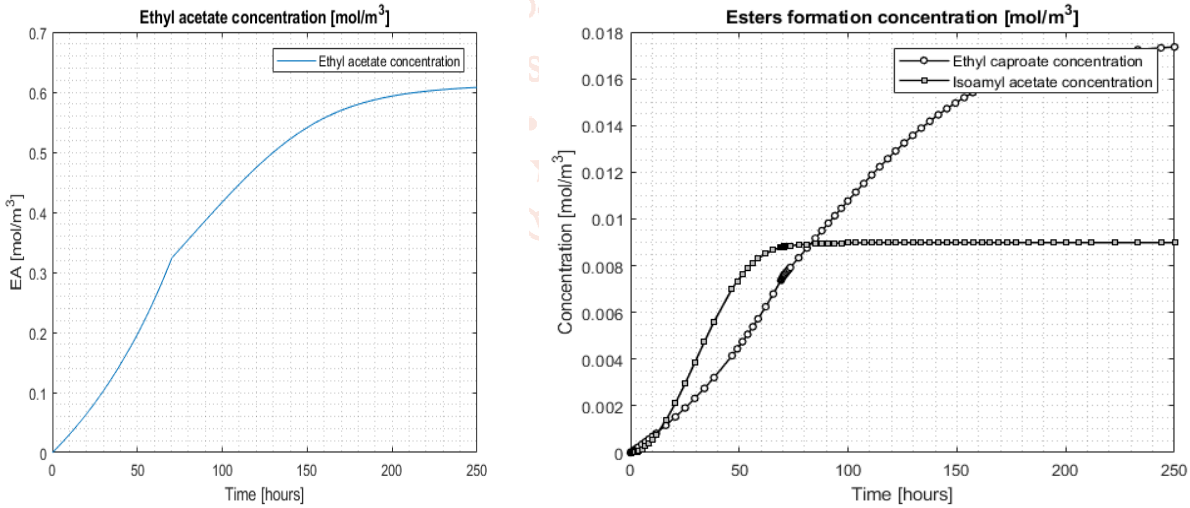

Figure 3.8 Esters model simulated result at temperature 18 °C, pitching rate 50 Mol/m³ and 200 Mol/m³, 320 Mol/m³ and 100 Mol/m³ concentration (initial) for glucose, maltose and malt triose respectively.

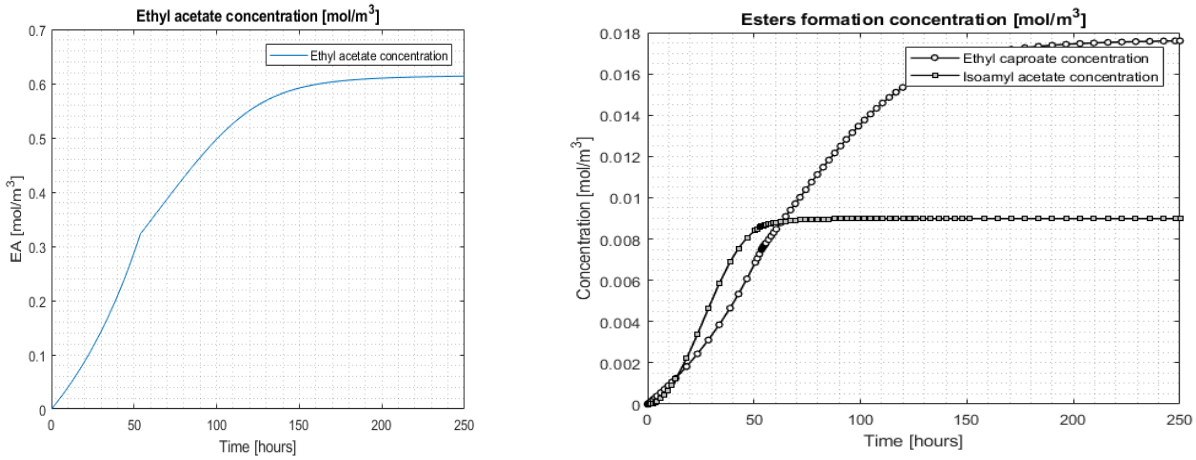

Figure 3.9Esters model simulated result at temperature 20 ^{O}C, pitching rate 50 Mol/m^3 and 200 Mol/m^3, 320 Mol/m^3 and 100 Mol/m^3 concentration (initial) for glucose, maltose and malt triose respectively.

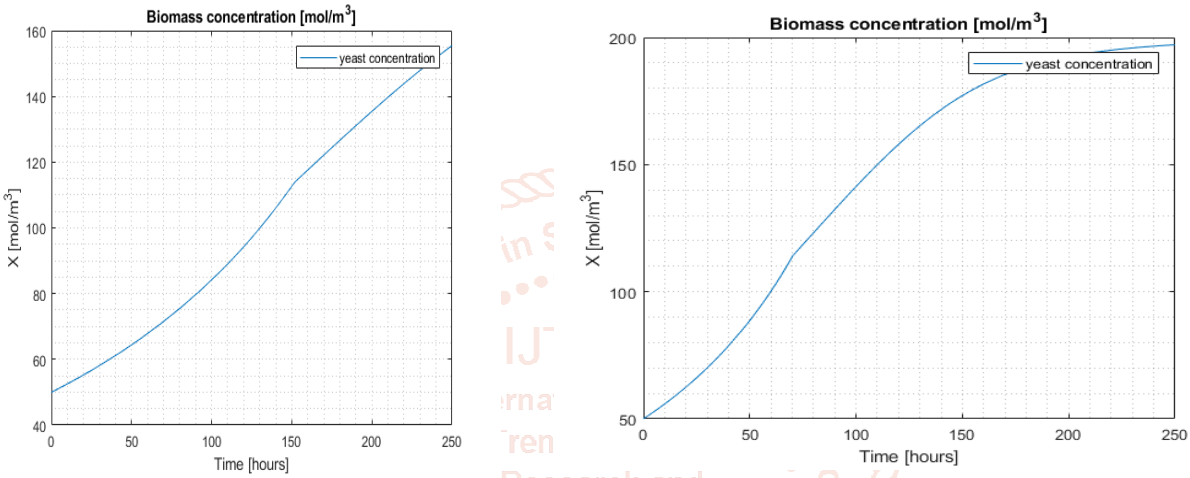

Figure 3.10Simulated result of yeast at 12.5^{O}C, 50 Mol/m^3 pitching rate and 1.3 Mol/m^3, 0.6 Mol/m^3 and 2.1 Mol/m^3 concentration for isoluicine, luicine and Valine respectively.

Figure 3.11Simulated result of yeast and ethanol at 18^{o}C, 50 Mol/m^{3}pitching rate and 1.3 Mol/m3, 0.6 Mol/m3 and 2.1 Mol/m3 concentration for isoluicine, luicine and Valine respectively.

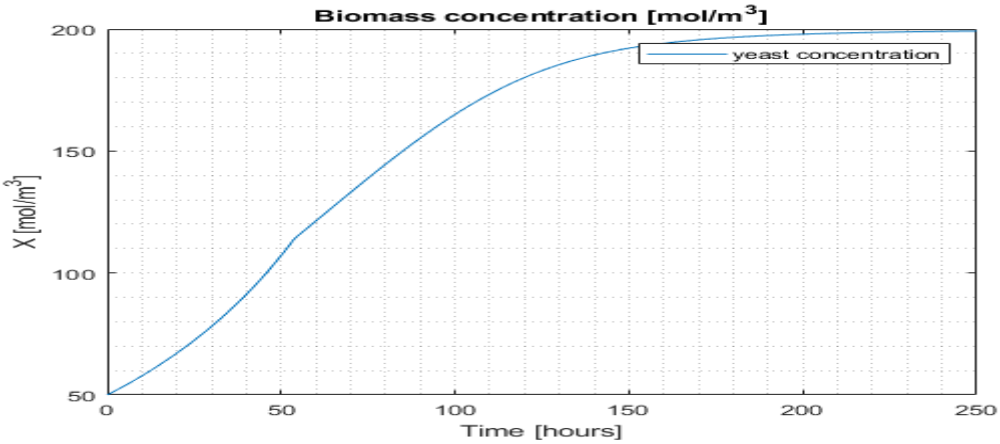

Figure 3.12Simulated result of yeast and ethanol at 20^{o}C, 50 Mol/m^3 pitching rate and 1.3 Mol/m3, 0.6 Mol/m3 and 2.1 Mol/m3 concentration for isoluicine, luicine and Valine respectively.

4. MODEL VALIDATION

To see the accuracy of the generated data, validation of the model had been necessary by comparing with already existed data or experimental data. In this case, the experiment was done to compare experimental value with a numerical value. Accordingly, for heat transfer model, temperature profile was collected along the arc length of the tank of the experimental staff at 1.4 coolant flow rate (current coolant flow rate) and compared with the modeled results as follows.

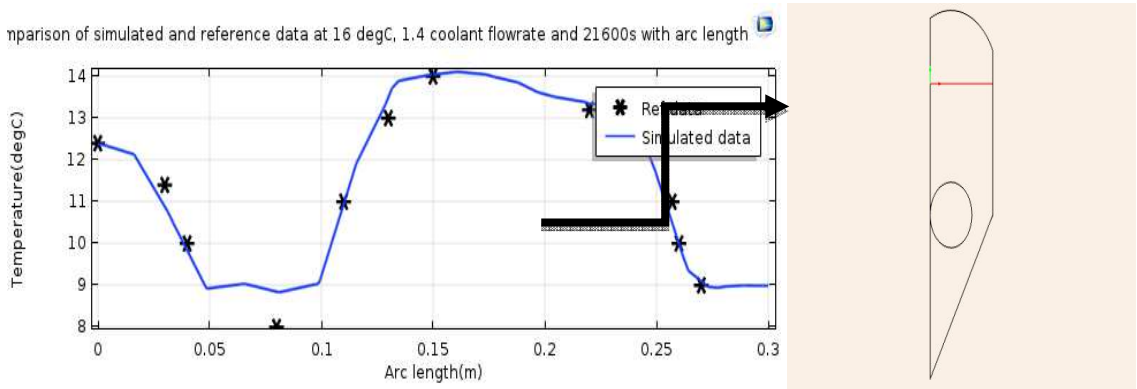

Figure 4.1 Comparison of simulated and experimental data at 16°C, 1.4m³/hr coolant flow rate and 21600 second along arc length

5. Conclusion

The beer fermentation process has been modeled by having a phenomenon that can be representative of beer fermentation. Energy balance was done to have a temperature profile with fermentation time. Relevant kinetics were developed for yeast growth, nutrients and esters model and simulated by incorporating operating parameter like temperature.

The finite element method was used to solve energy balance that has solved from an energy balance at a different coolant flow rate of ammonia coolant. The modeled result was indicating that as the coolant flow rate decreased, the temperature profile with fermentation time was increased. 1.2 m³/hr, 1.3 m³/hr, and 1.6 m³/hr were the selected coolant flow rates to see temperature profiles with fermentation time. This is due to of that, most of the brewery share company used 1.4 *m³/hr* coolant flow rate currently which the study wants to vary up and down from the current one. The temperatures that were observed at 1.2 m³/hr, 1.3 m³/hr and 1.6 *m³/hr* coolant flow rate were 20°C, 18°C and 12.5°C respectively with fermentation time.

The modeled kinetics of flavors (esters), nutrients and growth (yeast) model were simulated with the above temperatures to see its effect on fermentation time and beer flavor quality. The simulated results were indicated that in 20°C time to reach a flavor threshold value and time of Valine, luicine and isoluicine consumption wereshorter than the other two temperatures.

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LIST OF ABREVIATION

E	Ethanol concentration (mol/m^3)
FE	Finite Element
G	Glucose concentration (mol/m^3)
IA	Isoamyl alcohol concentration (mol/m^3)
IAc	Isoamyl acetate concentration (mol/m^3)
IB	Isobutyl alcohol concentration (mol/m^3)
M	Maltose concentration (mol/m^3)
MATLAB	Matrix Laboratory
MB	2-methyl-1-butanolconcentration (mol/m^3)
N	Malt triose concentration (mol/m^3)
P	n- propanol concentration (mol/m^3)

LIST OF SYMBOLS

ΔH_{FG}	Over all heat of formation for glucose (kJ/mol)
μ_1	Specific rate of glucose uptake (h^{-1})
μ_2	Specific rate of maltose uptake (h^{-1})
μ_3	Specific rate of malt triose uptake (h^{-1})
μ_i	Maximum reaction velocity for i^{th} sugar (i= G, M or N, h^{-1})
μ_I	Specific rate of isoluicine uptake (h^{-1})
μ_l	Specific rate of luicine uptake (h^{-1})
μ_{IA}	Specific rate of isoamyl alcohol formation (h^{-1})
μ_{io}	Arrhenius frequency factor for maximum velocity (h^{-1})
μx	Specific rate of yeast growth (h^{-1})
A	Area of heat transfer (m^2)
Cp	Specific heat capacity of wort (kJ/kg ^{0}C)
D	First order time delay (Michiko, Hiroshi, & Suteaki)
$E\mu i$	Arrhenius activation energy for maximum velocity (cal/mol)
$E'\mu i$	Arrhenius activation energy for inhibition constant (cal/mol)
E_{ki}	Arrhenius activation energy for michaelis constant (cal/mol)
K_{AAl}	Effective first order rate constant for uptake of AAl (m^3/mol h)
Ki	Michaelis constant for i^{th} sugar (i = G, M or N, mol/m^3)
K'i	Michaelis constant for i^{th} sugar (i = G, M or N, mol/m^3)
Kio	Arrhenius frequency factor for michaelis constant (mol/m^3)
K'io	Arrhenius frequency factor for inhibition constant (mol/m^3)
K_X	Empirical yeast growth inhibition constant (mol/m^3)^2
Q	Rate of heat flow (kJ/mol h)
R	Gas constant (cal/mol K)
t	Time(Michiko et al.)
T	Temperature (^{o}C)
U	Heat transfer coefficient (W/$m^2{}^o$C)
X	Biomass concentration (mol/m^3)
X_0	Initial yeast concentration (mol/m^3)
Y_{EG}	Yield coefficient, mole E per Mole G
Y_{EM}	Yield coefficient, mole E per Mole M
Y_{EN}	Yield coefficient, mole E per Mole N
Y_{XG}	Yield coefficient, mole X per Mole G
Y_{XM}	Yield coefficient, mole X per Mole M
Y_{XN}	Yield coefficient, mole X per Mole N
ρ	Density of wort (kg/m^3)