Journal of the Nigerian Association of Mathematical Physics
Volume 31, **(July, *2015*), pp 195 – 200**

Modelling Energy Effects During Ethanol Fermentation Coupled with *in situ* Gas Stripping

Amenaghawon N.A, Osazuwa U.O. and Osayuki-Aguebor W.

Department of Chemical Engineering, Faculty of Engineering, University of Benin, PMB 1154, Benin City, Nigeria.

Abstract

The growth of microbial cells during conventional batch ethanol fermentation is inhibited by high concentrations of ethanol. This problem could be alleviated by continuous removal of ethanol from the broth during fermentation and this could increase productivity and potentially reduce the cost of ethanol recovery. Energy effects during batch ethanol fermentation coupled with in situ gas stripping was investigated in this study using a mathematical model. The model which was formulated from energy balance equations was simulated to investigate the effect of gas stripping on some energy variables during fermentation. Results obtained showed that some degree of cooling was introduced by the stripping gas. However, the maximum temperature reduction was 3.5% which did not result in a significant degree of cooling. The amount of metabolic heat generated as well as the heat lost via aeration was observed to increase with increase in stripping gas flow rate. These observations were attributed to the alleviation of product inhibition during fermentation. The energy required for gas compression was observed to also increase with respect to the stripping gas flow rate.

Keywords: Modelling, Bioethanol, Fermentation, *Geobacillusthermoglucosidasius*, Gas stripping.

Nomenclature

C_{PL}	Liquid phase specific heat capacity (J/kg^{o}C)
C_{PG}	Gas phase specific heat capacity (J/kg^{o}C)
C_X	Microbial cell concentration (g/L)
D_s	Diameter of impeller (m)
D_t	Diameter of fermenter (m)
F_G	Stripping gas flow rate (L/h)
h_{conv}	Convectional heat transfer coefficient (W/^{o}C)
k	Liquid phase thermal conductivity (W/kg^{o}C)
m	flow rate of heating fluid (kg/s)
N_P	Power number
N_S	Impeller speed (rev/s)
Pr	Prandtl number
Q_{agit}	Energy required for agitation (W)
$Q_{aeration}$	Energy lost via aeration (W)
Q_{conv}	Energy lost via convection (W)
Q_{evap}	Energy lost via evaporation (W)
Q_{jacket}	External heat energy input (W)
Q_{input}	Energy input (W)
Q_{met}	Metabolic heat generated (W)
Q_{output}	Energy output (W)
Re	Reynolds number
t	time (h)
T_{bL}	Bulk liquid temperature (^{o}C)
T_G	Bulk gas temperature (^{o}C)
V_L	Volume of the liquid phase (L)
ΔH_{met}	Specific metabolic heat generated (J/kg)
ΔHv	specific enthalpy of vapourisation (J/kg)
ρ_L	Liquid phase density (kg/m^3)
ρ_G	Gas phase density (kg/m^3)
μ_L	Liquid phase viscosity (Pa.s)
λ_w	Latent heat of vapourisation of water (J/g)

1.0 Introduction

As a result of the environmental and energy security challenges associated with the use of conventional petroleum based fuels for transportation, a rapid expansion has been recorded in the market for bioethanol either as a blend with gasoline to enhance octane rating or as a primary fuel [1]. Production of bioethanol from abundantly available and low cost lignocellulosic

Corresponding author: Amenaghawon N.A, E-mail: andrew.amenaghawon@uniben.edu, Tel.: +2348069275563

biomass has been considered to be attractive and sustainable [2]. Bioethanol has conventionally been produced via batch fermentation of sugar substrates using the most common fermenting organism *Saccharomyces cerevisiae*. The ethanol produced is subsequently recovered from the fermentation broth and then concentrated by distillation [3].

The conventional batch fermentation process is limited by product inhibition introduced by ethanol toxicity to the fermenting microorganism and thermal instability of the microorganism[4]. The problem of product inhibition could be alleviated by continuous removal of ethanol during fermentation. *In situ* gas stripping using an inert gas is a viable alternative that has been proposed for recovering ethanol from fermentation broths [4-7]. Removal of ethanol via *in situ* gas stripping can alleviate the problem of product inhibition, increase the cell concentration in the broth, the ethanol productivity, substrate utilisation as well as reducing the cost of product concentration and purification. *In situ* gas stripping makes it possible to have a more concentrated glucose substrate as feed to the fermenter. The problem of periodical cleaning encountered with other methods is not encountered with gas stripping and the fermentation product is usually cleaner.

The problem of thermal instability of the microorganism could be solved by the use of thermally stable microorganisms such as thermophilic ethanol producing bacteria which can thrive at elevated temperatures[8]. The use of thermophilic ethanologenes presents certain advantages. There is the potential for using a wider range of substrates, energy savings through reduced cooling costs, higher saccharification and fermentation rates, reduced risk of contaminationetc [9]. Furthermore, using thermophilic microorganisms make it possible to also carry out the fermentation process close to the boiling point of ethanol, a situation that generally favours gas stripping as a recovery method [8]. In addition, ethanol production at high temperature is effective in tropical countries where average day-time temperatures are usually high throughout the year [10].

Because fermentation is an exothermic process, it is important to consider heat or energy effects during the process. Energy transfer during fermentation could occur via a host of processes such as metabolic heat generation, aeration, mixing, cooling, heating etc. The bacterium *Zymomonas mobilis* and yeast *Saccharomyces cerevisiae* have been reported to gain the energy required for growth and maintenance under anaerobic conditions by substrate phosphorylation processes through the Entner-Doudoroff pathway and glycolysis respectively [9]. Energy is usually required to accomplish efficient mixing during fermentation [11]. In some instances, cooling is required and heat generation by exothermic sugar fermentation by thermophilic microorganisms has an impact on the net heat balance vis-a-vis cooling water requirement in such fermentation processes [9,12]. Hence, with the multifactor activities occurring inside the fermentation vessel, energy consideration becomes important.

Dynamic modelling of the fermentation process enables the representation of the process in a mathematical sense. Simulation of formulated models can be utilised in analysing the dynamic behaviour of the process under consideration, provision of insights into the mechanisms that drive the process, understanding the response of the process to changes in operating conditions, design of controllers and design of entirely new processes [13]. Hence, the aim of this study is to analyse energy transfer effects during an ethanol fermentation process coupled with gas stripping.

2.0 Materials and Methods

2.1 Microorganism and Fermentation Conditions

The thermophilic ethanol producing microorganism *Geobacillusthermoglucosidasius* obtained from the biotechnology division of the Federal Institute of Industrial Research Oshodi (FIIRO), Lagos, Nigeria was used as the fermenting microorganism. A freeze-dried culture of *Geobacillusthermoglucosidasius* was revived by aseptically adding 0.3 mL of fresh anaerobic medium to a single-vial and transferring the total mixture to a 5 mL McCartney bottle (BDH, UK) with a working volume of 3 mL. It was ensured that anaerobic conditions prevailed during the transfer by making use of the modified Hungate technique [14]. Stock cultures for subsequent use were prepared by adding 10 mL of fermentation broth from mid-exponential growth phase to a 28 mL Mc Cartney (BDH, UK) bottle with 10 mL sterile anaerobic glycerol. These stocks were stored at -20 °C for subsequent use. The composition of the fermentation medium is the same as that previously reported by Hild [15].

2.2 Batch Fermentation and Gas Stripping

A 2 L bioreactor with a working volume of 1.5 L was used for the batch fermentation process which was allowed to proceed for about 21 hours. An anaerobic environment was created by purging the reactor system with oxygen-free nitrogen gas [16]. Gas stripping was initiated by pumping oxygen-free nitrogen gas through the system at a gas flow rate of 30 L/h using a twin-head peristaltic pump. The ethanol vapours were cooled in a condenser using 50% ethylene glycol. A schematic diagram of the integrated bioreactor set up is shown in Figure 1.

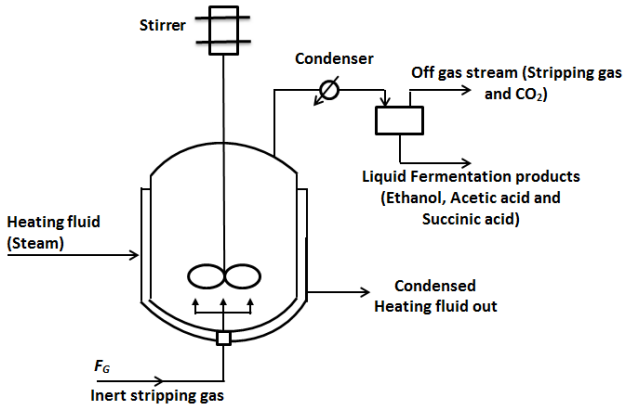

Figure 1: Schematic diagram of batch fermentation process coupled with gas stripping

2.3 Analytical Methods

The amount of ethanol produced was analysed using a gas chromatography system equipped with a flame ionisation detector (GCD-Gas chromatograph, Pye Unicam UK). The column employed was a 1.5 meter glass column with Porapak Q 80/100 mesh as the stationary phase. The temperature for detector, injector and column were set to 200 °C, 200 °C and 150 °C respectively. Standards of known ethanol concentration were made up with anhydrous ethanol and deionised water. A predetermined amount of the sample (1µL) was injected into the column and the peak areas were determined by using a programmable integrator (HP3390A, Hewlett Packard UK).

2.4 Energy Balance Equations

The general energy balance equation for the fermenter can be written as [17]:

$$\rho_L V_L C_{pL} \frac{dT_{bL}}{dt} = Q_{input} - Q_{output} \quad (1)$$

For the integrated system of simultaneous fermentation and ethanol removal via gas stripping to function, the process needs to be operated close to the boiling point of ethanol. Hence a heating jacket is required to maintain the temperature of the process at the desired set value. The external heat input into the system was estimated using Equation (2).

$$Q_{jacket} = \dot{m}\Delta H_v \quad (2)$$

$\dot{m}$ (kg/s) is the flow rate of the heating fluid (steam in this case) and ΔH_v (J/kg) is the specific enthalpy of vapourisation of the heating fluid. Energy in the form of heat is generated as a result of the metabolic action of the microorganism in converting the carbon substrate to ethanol and other products. This is defined as follows [17]:

$$Q_{met} = V_L \mu_L C_X \Delta H_{met} \quad (3)$$

ΔH_{met} is the specific metabolic enthalpy (J/g).

The energy transferred into the system through agitation by the stirrer is a function of the stirrer speed and diameter and is defined as follows:

$$Q_{agit} = N_p \rho_L N_s^3 D_s^5 \quad (4)$$

N_p, N_s (rev/s) and D_s (m) refer to the power number, stirrer speed and stirrer diameter respectively.

The externally added energy input is comprised of Q_{jacket}, Q_{met} and Q_{agit}.

Energy equations were also formulated in a similar manner for energy lost from the system. The fermentation process is operated at a temperature of about 60 ^oC, while the temperature of the stripping gas is set at about 25 ^oC. As a result, the system experiences heat losses due to the temperature difference between the fermenter and the stripping gas stream. Hence, energy losses in the form of heat could occur through aeration, convection and evaporation and these were defined as follows:

$$Q_{aeration} = F_G \rho_G C_{pG} (T_{Lb} - T_G) \quad (5)$$

C_{pG} (J/kgK) is the specific heat capacity of the stripping gas and T_G (K) is the temperature of the inert stripping gas.

$$Q_{conv} = h_{conv} (T_{Lb} - T_G) \quad (6)$$

$$Q_{evap} = F_G \lambda_w (H_{Go} - H_{Gi}) \quad (7)$$

λ_w is the latent heat of vapourisation of water.
The convective heat transfer coefficient h_{conv} is defined as follows [18]:

$$h_{conv} = 0.74\frac{k}{D_t}Re^{0.67}Pr^{0.33}\left(\frac{\mu_l}{\mu_w}\right)^{0.14} \quad (8)$$

D_t (m) is the diameter of the fermentation vessel. The dimensionless Reynolds number (Re) and Prandtl number (Pr) are respectively defined as follows:

$$Re = \frac{N_s D_s^2 \rho_L}{\mu_L} \quad (9)$$

$$Pr = \frac{C_{pL}\mu_L}{k} \quad (10)$$

k (W/mK) is the thermal conductivity of the liquid phase.
Combining the terms representing the external energy inputs as well as the energy losses from the system results in the following equation describing the conservation of energy inside the fermenter.

$$\rho_L V_L C_{pL}\frac{dT_{bL}}{dt} = Q_{jacket} + Q_{met} + Q_{agit} - Q_{aeration} - Q_{conv} - Q_{evap} \quad (11)$$

C_{pL} (J/kgK) is the specific heat capacity of the liquid phase and T_{bL} (K) is the temperature of the bulk liquid phase.
In order to investigate the dynamic behaviour of the batch fermentation process, the system of energy balance equations was solved numerically and the data presented in Table 1 was used for simulation.

Table 1: Parameter values for dynamic simulation

Parameter	**Value**	**Source**
Broth specific heat capacity Cp_L	2500 J/kg^{o}C	Sweat [19]
Broth thermal conductivity k	0.3 W/kg^{o}C	Van Lier et al. [20]
Convective mass transfer coefficient h_m	0.276 m/h	Calderbank and Moo-Young [21]
Fermenter volume V_L	1 L	Hild [15]
Gas density ρ_G	1.145 g/L	Perry et al. [22]
Gas specific heat capacity C_{pG}	1040 J/kg^{o}C	Perry et al. [22]
Impeller diameter D_s	0.0058 m	Joshi et al. [23]
Impeller speed N_s	1.67 1/s	Joshi et al. [23]
Liquid phase density ρ_L	991 g/L	Hild [15]
Liquid phase viscosity μ_L	0.0013 $Pa.s$	Hild [15]
Metabolic heat generated ΔH_{met}	22440 J/g	Perry et al. [22]
Power number N_P	0.7	Joshi et al. [23]
Specific latent heat of evaporation λ_w	1814.46 J/L	Perry et al. [22]
Temperature of stripping gas T_G	30^{o}C	Hild [15]
Universal gas constant R	8.314 J/mol^{o}C	Perry et al. [22]

3.0 Results and Discussion

Figure 2 shows that the temperature of the bulk liquid phase reduced with time in the course of fermentation irrespective of the flow rate of gas used. The reduction in temperature could be attributed to the cooling effect of the stripping gas. Because the stripping gas enters the fermenter at a temperature of about 25^{o}C and the fermentation process is operated at about 60^{o}C to favour gas stripping, there will be some level of cooling which is evident in the reduction in the temperature of the system. The maximum temperature reduction should not be too significant to result in the need for extra heating which in turn will increase the cost of the process. The results presented in Figure 2 shows that the maximum temperature reduction was obtained as 3.5% which does not translate to a significant degree of cooling.
The effect of fermentation time and stripping gas flow rate on the amount of heat generated as a result of metabolic action of the fermenting organism is shown in Figure 3. A quadratic relationship was observed between the metabolic heat released and the fermentation time. The metabolic heat released was observed to increase with increase in gas flow rate. Microbial fermentation is an exothermic process in which metabolic heat is released as the microbial cell population utilise the available carbon substrate to produce metabolic products.

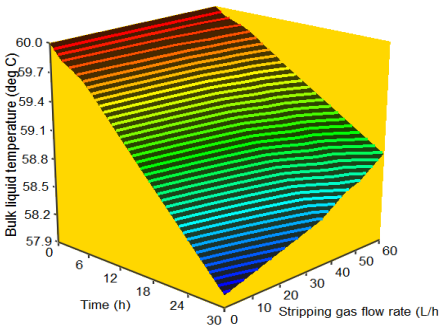

Figure 2: Effect of fermentation time and gas flow rate on bulk liquid phase temperature

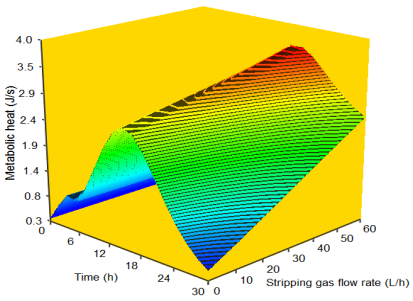

Figure 3: Effect of fermentation time and gas flow rate on metabolic heat generation

As the gas flow rate is increased, more of the ethanol is stripped from the fermentation broth which results in a decrease in the concentration of ethanol in the liquid phase. With the level of ethanol lowered below inhibitory levels, the cells are able to function optimally and the fermentation process can be continued for long periods. This consequently results in the generation of more metabolic heat.

The heat lost as a result of the aerating effect of the stripping gas increased with increase in stripping gas flow rate as shown in Figure 4. Since the temperature of the stripping gas is less than that of the fermentation broth, the temperature difference results in some cooling effect and this typically increases as more gas is delivered into the fermentation vessel. For gas stripping to be employed as an effective recovery system, the temperature of the fermentation broth has to be close to the boiling point of ethanol. Hence, it is important to monitor the degree of cooling introduced as a result of aeration so as not to introduce the need for reheating the fermenter contents which will further contribute to the cost of the process.

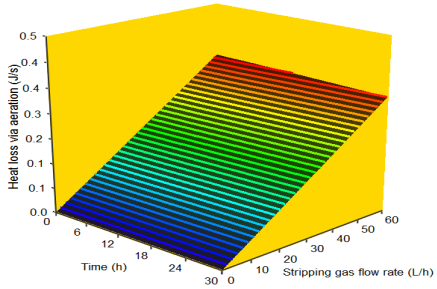

Figure 4: Effect of fermentation time and gas flow rate on heat loss through aeration

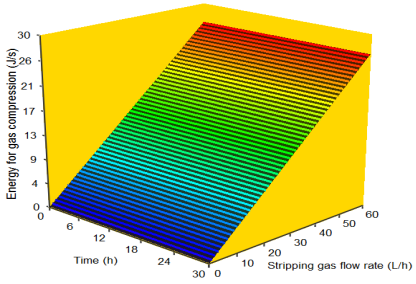

Figure 5: Effect of fermentation time and gas flow rate on energy required for gas compression

In order to convey the stripping gas through the fermenter, it needs to be compressed. Compression of the gas is also necessary in order to attain the pressure required to create bubbles which are important in creating the necessary interfacial surface areas for mass transfer [24]. Furthermore, the gas bubbles created reduces the energy requirement for mixing the fermenter content by reducing the density of the fluid and influencing the hydrodynamic behaviour of the fluid around the agitator [11]. The compressor requires electrical power to function and the energy requirement of gas compression is dependent on the amount of gas the compressor can deliver for a given period. Figure 5 shows the simulation results obtained by varying the fermentation time and stripping gas flow rate. The results show that there was no significant change in the energy required for gas compression with respect to time. However, the energy required for gas compression was observed to increase linearly and progressively with increase in stripping gas flow rate. Higher gas flow rates were required to achieve high stripping rates. Hence, one would expect to use the maximum allowable gas flow rate. Nevertheless, Figure 5 shows that the higher the gas flow rate, the higher the energy requirement for gas compression hence a higher cost of operation. To have an economically viable production process, the cost of ethanol production should be competitive. In the light of this, there has to be a trade-off between efficient separation and recovery (sufficient ethanol removal from the liquid phase) and separation process economics which can establish non inhibitory ethanol concentrations in the liquid phase and an ideal ethanol concentration in the condensate so that the entire process would be energy attractive.

4.0 Conclusion

Energy effects during batch ethanol fermentation were investigated in this study. A system of differential and algebraic equations was formulated to represent the energy effect during fermentation. Some level of cooling was observed during fermentation as a result of the introduction of the stripping gas. However, the maximum temperature reduction was 3.5% which does not translate to a significant degree of cooling. Increasing the stripping gas flow rate results in an increase in the generation of metabolic heat. Heat loss via aeration increases with increase in stripping gas flow rate while the energy

required for gas compression also increases with respect to the stripping gas flow rate. The model presented in this work though able to describe energy transfer effects during fermentation, can be extended to derive a predictive model. However, reliable correlations for gas/liquid interfacial areas and heat transfer coefficients applicable during fermentation will have to be developed.

References

[1] Mohan, P.R. and Reddy, O.V.S. (2012). Production and Optimisation of Ethanol from Pretreated Sugarcane Bagasse using *Saccharomyces bayanus* in Simultaneous Saccharification and Fermentation. *Microbiology Journal*, 2(2), pp. 52–63.

[2] Sakar, N., Ghose, S.K., Banerjee, S. and Aikat, K. (2012). Bioethanol production from agricultural wastes: An overview. *Renewable Energy*, 37, pp. 19–27.

[3] Amenaghawon, N. A., Aisien, F. A., and Ogbeide, S.E. (2013). Bioethanol Production from Pretreated Cassava Bagasse using combined Acid and Enzymatic Hydrolysis. *University of Benin Journal of Science and Technology*, 1(2), pp. 48-53.

[4] Taylor, F., Kurantz, M. J., Goldberg, N. and Craig, J.C. (1998). Kinetics of continuous fermentation and stripping of ethanol. *Biotechnology Letters*, 20(1), pp.67–72.

[5] Dominguez, J.M., Cao, N., Gong, C.S. and Tsao GT. (2000). Ethanol production from xylose with the yeast *Pichia stipitis* and simultaneous product recovery by gas stripping using a gaslift loop fermentor with attached side-arm (GLSA). *Biotechnology and Bioengineering*, 67, pp. 336–343.

[6] Ezeji, T.C., Karcher, P.M., Qureshi, N. and Blaschek, H.P. (2005). Improving performance of a gas stripping-based recovery system to remove butanol from Clostridium beijerinckii fermentation. *Bioprocess and Biosysthesis Engineering*, 27, pp. 207–214.

[7] Liu, J., Fan, L.T., Seib, P., Friedler, F. and Bertok B. (2004). Downstream process synthesis for biochemical production of butanol, ethanol, and acetone from grains: generation of optimal and near-optimal flowsheets with conventional operating units. *Biotechnology Progress*, 20, pp. 1518–1527.

[8] Hild, H.M., Stuckey, D.C. and Leak, D.J. (2003). Effect of nutrient limitation on product formation during continuous fermentation of xylose with *Thermoanaerobacter ethanolicus* JW200 Fe(7*). Applied Microbiology and Biotechnology*, 60, pp. 679-686.

[9] Kumar, S., Dheeran, P., Singh, S. P., Mishra, I. M. and Adhikari, D. K. (2013). Cooling system economy in ethanol production using thermotolerant yeast *Kluyveromyces sp*. IIPE453. *American Journal of Microbiological Research*, 1(3), pp. 39-44.

[10] Limtong, S., Sringiew, C. and Yongmanitchai, W. (2007). Production of fuel ethanol at high temperature from sugar cane juice by a newly isolated *Kluyveromyces marxianus*. *Bioresource Technology*, 98(17), pp. 3367-3374.

[11] Fadavi, A. and Chisti, Y. (2005). Gas–liquid mass transfer in a novel forced circulation loop reactor. *Chemical Engineering Journal*, 112(1), pp. 73-80.

[12] Magazoni, F. C., Monteiro, J. B., Colle, S. and Cardemil, J. M. (2010). Cooling of ethanol fermentation process using absorption chillers. *International Journal of Thermodynamics*, 13(3), pp. 111-118

[13] Amenaghawon, N.A. and Okieimen, C.O. (2012). Modelling and Simulation of Thermal Decomposition of Acetylated Castor Oil in a Non-Isothermal Reactor. *Journal of Engineering and Applied Sciences*, 8(1), pp. 45-52

[14] Hungate, R.E. (1969). A roll tube method for cultivation of strict anaerobes. *Methods in microbiology*, 3B, pp. 117-132.

[15] Hild, H.M. (1998). Thermophilic ethanol production in a novel gas-stripping fermenter. *PhD Thesis*, Imperial College London.

[16] Cripps, R.E., Eley, K., Leak, D.J., Rudd, B., Taylor, M., Todd, M., Boakes, S., Martin, S. and Atkinson, T. (2009). Metabolic engineering of *Geobacillus thermoglucosidasius* for high yield ethanol production. *Metabolic Engineering*, 11(6), pp. 398-408.

[17] Bailey, J.E. and Ollis, D.F. (1986). *Biochemical engineering fundamentals*. McGraw Hill Book Company.

[18] Treybal R.E. (1981). *Mass transfer operations*. McGraw-Hill Book Company.

[19] Sweat, V.E. (1986). *Thermal properties of foods*. Engineering properties of foods, pp. 49–132.

[20] Van Lier, J.J.C., Van Ginkel, J.T., Straatsma, G., Gerrits, J.P.G. and Van Griensven, L.J.L.D. (1994). Composting of mushroom substrate in a fermentation tunnel: compost parameters and a mathematical model. *NJAS Wageningen Journal of Life Sciences*, 42(4), pp. 271-292.

[21] Calderbank, P.H. and Moo-Young, M.B. (1995). The continuous phase heat and mass transfer properties of dispersions. *Chemical Engineering Scie*nce, 50(24), pp. 3921-3934.

[22] Perry, R.H., Green, D.W. and Maloney, J.O. (1997). *Perry's chemical engineers' handbook*, McGraw-Hill.

[23] Joshi, J., Pandit, A. and Sharma, M. (1982). Mechanically agitated gas-liquid reactors. *Chemical Engineering Science*, 37(6), pp. 813-844.

[24] Mirón, A.S., Camacho, F.G., Gómez, A.C., Grima, E.M. and Chisti, Y. (2000). Bubble-column and airlift photobioreactors for algal culture. *AIChE Journal*, 46(9), pp. 1872-1893