Oxygen transfer to cassava starch solutions in an aerated, well-mixed bioreactor: Experimental and mass transfer studies

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Abstract−Experimental and mass transfer studies of oxygen transfer to cassava starch solution in an aerated, well-mixed bioreactor of 2 L have been carried out. The volumetric mass transfer coefficient was estimated and parametric studies were performed to study the effect of process variables of stirring rate, aeration rate, concentration of starch and temperature on the volumetric mass transfer coefficient. From the experimental results, it is evident that the first two and the last variables are directly proportional to the volumetric mass transfer coefficient. However, the volumetric mass transfer coefficient is inversely proportional to the concentration of the starch. Also, the saturation dissolved oxygen concentration is greatly affected by temperature and starch solution concentration. Whereas, stirring and aeration rates have neutral impacts on saturation dissolved oxygen concentration. Simulated data generated from obtained volumetric mass transfer coefficient agrees well with the experimental data, which indicates the accuracy of the coefficient.

Keywords: Bioreactor, Cassava Starch, Mass Transfer Studies and Volumetric Mass Transfer Coefficient

INTRODUCTION

Global demand for energy continues to grow due to rapidly expanding human population and increasing industrial prosperity in developing countries. Energy security, declining oil reserves, unstable oil market price and climate change have served as drivers for new initiatives to increase alternative fuel sources. Alternative to petroleum-derived fuels are being sought to reduce the world's dependence on non-renewable sources, and the most common renewable fuel today is liquid biofuel, principally bioethanol. The growing interest in energy alternatives for fossil fuels has boosted ethanol production worldwide from 33 billion liters to 88.7 billion liters in the period of 2005-2011 [1]; it is estimated that in 2015 the production will be around 115 billion liters [2]. Bioethanol can be used as an alternative fuel in the form of fuel-ethanol (pure alcohol) as a sole fuel in cars with dedicated engines or can be blended with gasoline with no engine modification requirement when mixed up to 30% [2,3]. Bioethanol is also produced from agricultural crops, which are able to remove CO_2 (greenhouse gas) from the atmosphere [3, 4]. For these reasons, today bioethanol is the most used non-fossil alternative engine fuel in the world.

Bioethanol is produced from the fermentation of biological feedstocks that contain sugar or materials that can be converted into sugar. Therefore, bioethanol feedstocks can be classified into three types: sugars/sucrose, starches and lignocellulosic materials [3,4]. The first two are categorized as the first generation of bioethanol, and the last is the second generation bioethanol. Theoretically, second gen-

eration bioethanol, derived from lignocellulosic substrates, can reduce the food vs. fuel conflict since it can be produced from non-food crops. Moreover, lower raw material cost is expected if the feedstocks are lignocellulosic wastes. However, many challenges associated with raw material collection, pretreatment and cost of enzyme for hydrolysis and recovery of the ethanol from the low concentration produced in the fermenter still hinder the realization of large scale, commercial production of bioethanol from the lignocellulosic materials [4,7,8,12]. Intense research is still being carried out to make the second generation bioethanol technology economically viable, but to date no major breakthrough has been proposed for commercial scale. Consequently, the majority of the fuel ethanol produced in the world is currently sourced from sucrose, such as molasses and cane juice, and starch such as corn/maize, cassava and wheat [2,5-11]. In fact, the choice of raw material depends on the local condition. For countries in South East Asia like Indonesia and Thailand, some promising feedstocks are available for bioethanol production: sugarcane juice, molasses, cassava, corn, sorghum, sweet potatoes and sago. Among these feedstocks, bioethanol is currently produced mostly from sugarcane juice, molasses and cassava [13-16]. More efforts, however, have been directed to the use of cassava for the raw material of bioethanol production. This is due to several reasons: high starch yield of cassava per hectare compared with other crops [4,17-19], all-year round availability of cassava due to flexible planting and harvesting [17,20], and lower input requirement in planting, drought resistant crop and easily grown in any types of soil conditions [16,20]. Some other positive characteristics of cassava starch are its low tendency to retrograde compared with other starches such as potato, rice and corn, high purity, neutral flavor, solubility and easily swollen property [21,22]. Cassava is also less used for food consumption, hence, it is preferable since it has fewer

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food vs. fuel issues. Another reason for Indonesia to focus on the utilization of cassava is its status as net importer of sugar; therefore, sugarcane processing is more directed toward fulfilling domestic need for sugar. Moreover, the production of monosodium glutamate in Indonesia normally uses molasses [21], so the use of molasses for bioethanol production is not favored. The United States is also considering moving toward cassava as bioethanol feedstock to reduce its reliance on corn-based bioethanol [18]. The same trend is also happening in other countries such as China, Nigeria, Mozambique, Ghana and Congo [23-25].

Two of the main steps in the bioconversion of cassava into bioethanol are hydrolysis (saccharification) and fermentation which normally occur in a stirred tank bioreactor [26,27]. One of the factors which may limit the productivity of bioconversion is mass transport of oxygen into the aqueous media inside the reactor. Oxygen is a key substrate to the growth and survival of the aerobic life in the bioprocess. Therefore, provision of sufficient oxygen supply and proper design of aeration system are essential. The main parameter

in the aeration process is volumetric mass transfer coefficient of oxygen, $K_L a$, which also serves as the most important parameter affecting the design and operation of the bioreactor. This coefficient must be known to assist the design, scaling up and optimization of the commercial scale bioreactor. Thus, precise knowledge of the oxygen mass transfer and reliable value of $K_L a$ are necessary.

Many investigators have studied oxygen mass transfer into liquid media and solutions in aerated, agitated vessels/columns as summarized by Table 1. Previous researches show that studies on oxygen mass transfer to starch/glucose solutions are very limited. In particular, to date, study on oxygen mass transfer to cassava starch solution is yet to be found. Coefficients obtained from different systems, e.g., from distilled water system, cannot be used in designing, scaling up, operating and optimizing the bioreactor for bioethanol production from cassava. This is because a cassava starch solution, even only at 2.5% cassava starch content, has higher viscosity than of water, as indicated by Table 2. Consequently, the rheological behavior of cassava starch solution is different with water where some

Table 1. Summary of previous research on the studies of oxygen mass transfer in aerated vessels/reactors

Finding	Liquid media/solutions	System	Ref.
$K_L a$ value and dimensionless correlation of $K_L a$	Water+xanthan gum	An aerated, agitated reactor	[26]
$K_L a$ values and the effects of aeration rate, solution viscosity and concentration to $K_L a$	Distilled water, distilled water+glycerol, distilled water+biomass support particle and distilled water+glycerol+biomass support particle	An aerated, agitated bioreactor	[27]
$K_L a$ values and effects of temperature and air flowrate	Tap water, an-aerobically pretreated paper process water and thermophilic sludge	An-aerated cylindrical column	[28]
Effects of surfactant and organic phase concentration to K_L	Emulsion of oil and water biphasic medium	A aerated column	[29]
$K_L a$ values and effects of aeration rate and impeller speed to $K_L a$	Reverse osmosis water and salt water	An aerated, agitated vessel	[30]
$K_L a$ value	Deionized water	An aerated, agitated bioreactor	[31]
$K_L a$ and effects of impurities on $K_L a$	water, water+soybean oil, water+sodiumdodecylbenzene and water+diatomaceous earth	An aerated vessel	[32]
$K_L a$ and dimensionless correlation for $K_L a$ prediction	Water and water+glycerol, soybean flour+$K_2 HPO_4$ +$MnCl_2 \cdot 4H_2O$+$FeSO_4 \cdot 7H_2O$	An aerated, agitated bioreactor	[33]
$K_L a$, k_L and correlations between k_L and D	Water+NaCl, water+glucose and water+sodium lauryl sulphate	An aerated vessel	[34]
$K_L a$ and effect of temperature on $K_L a$	Water	An aerated vessel	[35]
DO dynamic and concentration profile	Water+granule sludge	An aerated, agitated reactor	[36]
DO dynamic and concentration profile	Wines	An aerated column	[37]
$K_L a$ and effects of impeller and dispersion device on $K_L a$	Water	An aerated, agitated vessel	[38]
Oxygen concentration profile	Water+calciumsulfite		[39]
$K_L a$ and effects of impeller geometry and power consumption on $K_L a$	Water	An aerated, agitated vessel	[40]
$K_L a$	Water+activated sludge	An aerated column	[41]
$K_L a$ and k_L	Water+Na_2SO_3, water+Na_2SO_3+Sokrat 44, water Na_2SO_3+short fiberCMC+water+Na_2SO_3+long fiber CMC, water+Na_2SO_3+PEG	An aerated, agitated tank and an aerated column	[42]
$K_L a$ and effects of impeller configuration, impeller speed, aeration rate, liquid viscosity and suspended solid on $K_L a$	Water, water+sodium CMC, water+sodium CMC +dextrose+PDP+DHP+MSH+urea+CCD	An aerated, agitated bioreactor	[43]

Table 2. Viscosity of solution at the different concentrations of cassava starch

Concentration of cassava, %	Viscosity, Pa·s	Ref.
0 (Water only)	0.001*	[44]
2.5	0.09-0.77**	[45]
5	1.1-6.3**	[45]
7.5	8.1-36.2**	[45]
10	8.9-92.6**	[45]

*At 30 $^{\circ}$C

**At 30-70 $^{\circ}$C and the values depend on the shear rate

research found that cassava starch solution behaves as non-Newtonian fluid and it fits the power law and Bingham models well [45, 46]. From the literature, most works on ethanol production from cassava used different concentrations of cassava starch solutions which vary from 1% to 40% [47-49]. At these ranges, cassava starch solutions definitely behave differently compared with water. These further justify the needs of having studies on the oxygen transfer to cassava starch solutions since research works on this area are scarce.

Our aim was to do a mass transfer study and to obtain K_La for mass transfer of oxygen in cassava starch solution. Moreover, parametric studies to investigate the effects of stirring rate, aeration rate, concentration of the starch, and temperature on K_La were conducted. It is envisaged that the results from this work can serve as an important parameter in designing, scaling up, operating and optimization of the bioreactor for bioethanol production from cassava.

MATERIALS AND METHODS

1. Chemicals and Reagents

The materials used in this experiment are cassava (tapioca) powder, distilled water, sodium sulfite, cobaltous chloride, hydrochloric acid and sodium hydroxide. Sodium sulfite and cobaltous chloride are used for oxygen reducing agent whereas hydrochloric acid and sodium hydroxideare pH controlling agents.
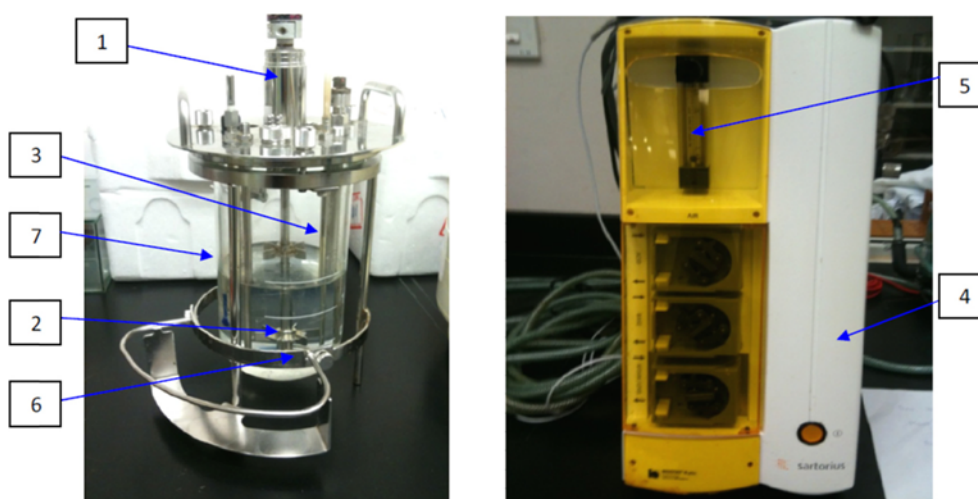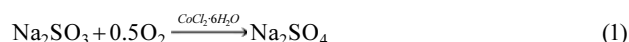
2. Bioreactor

All the experiments were carried out using a Sartorius A-Plus 2 L bioreactor as shown in Fig. 1. First, the bioreactor was calibrated. Major calibrations include DO and pH calibrations. The DO probe was calibrated until the saturation point of DO was set at 21%. The value of 21% represents atmospheric oxygen concentration since air aerated into the bioreactor is directly pumped from the atmosphere. Meanwhile, pH calibration was performed using buffer solutions of pH 4 and pH 10. The pH buffers of pH 4 and pH 10 were used, as these settings are fixed by the software embedded to the bioreactor. The pH probe attached in the bioreactor was immersed in a standard solution of pH 4 to calibrate the pH buffer of pH 4. Once it was done, the pH probe was also immersed into a standard solution of pH 10 to calibrate the pH buffer of pH 10. The pH calibration was considered successful when both calibrations were completed and had achieved the respective pH buffers by the bioreactor. The procedures of DO and pH calibrations were repeated before starting the new set of experiments.

3. Experimental Procedures

Sets of experiments involving investigations of the effects of aeration rate, impeller speed and temperature on the oxygen transfer at different concentration of cassava starch were carried out. Solutions of cassava starch at concentrations of 0%, 5%, 10% and 15% were prepared by adding required amount of dried cassava powder into deionized water at room temperature. Well-mixed suspensions in the bioreactor were sterilized by heating them at 121 $^{\circ}$C for 45 minutes and then rapidly cooled to room temperature. Once the sterilized starch solutions were cooled, concentrations of oxygen in these solutions were zeroed by adding sodium sulfite and cobaltous chloride. Amount of sodium sulfite needed was determined by combining stoichiometric relation and practical experiences from others [50]. The reaction between sodium sulfite and oxygen follows the reaction below where cobaltous chloride acts as catalyst.

$$Na_2SO_3 + 0.5O_2 \xrightarrow{CoCl_2 \cdot 6H_2O} Na_2SO_4 \qquad (1)$$

Fig. 1. Bioreactor used for the experimental works.
1. Motor of the stirrer   3. Dissolved oxygen (DO) meter   5. Gas flow meter   7. Reactor
2. Impeller   4. Control panel   6. Gas distributor

Table 3. Saturation DO concentration at different operating conditions

| Concentration, %	Aeration rate, L/min	Stirring rate, rpm	Temperature 37 °C				Temperature 45 °C			
			Replication (R)			C^* (Average), mg/L	Replication (R)			C^* (Average), mg/L
			C^* (R1), mg/L	C^* (R2), mg/L	C^* (R3), mg/L		C^* (R1), mg/L	C^* (R2), mg/L	C^* (R3), mg/L	
0	0.6	100	6.98	7.00	6.99	7.02	6.00	6.07	6.04	6.07
		300	7.02	7.03	6.99		6.04	6.10	6.04	
		500	7.08	7.06	7.07		6.10	6.13	6.12	
	1.2	300	7.00	6.99	7.01		6.02	6.06	6.06	
5	0.6	100	6.73	6.74	6.75	6.82	5.75	5.81	5.80	5.86
		300	6.77	6.79	6.78		5.79	5.86	5.83	
		500	6.91	6.89	6.88		5.93	5.96	5.93	
	1.2	300	6.83	6.86	6.85		5.85	5.93	5.90	
10	0.60	100	6.63	6.63	6.64	6.71	5.65	5.70	5.69	5.75
		300	6.69	6.69	6.69		5.71	5.76	5.74	
		500	6.79	6.78	6.79		5.81	5.85	5.84	
	1.2	300	6.71	6.71	6.71		5.73	5.78	5.76	
15	0.6	100	6.79	6.77	6.77	6.59	5.81	5.84	5.82	5.64
		300	6.61	6.60	6.58		5.63	5.67	5.63	
		500	6.52	6.51	6.52		5.54	5.58	5.57	
	1.2	300	6.47	6.46	6.46		5.49	5.53	5.51	

From the reaction above, theoretically 7.9 mg/L sodium sulfite is required for each mg/L of DO. However, as suggested by Stukenberg et al. [51], 1.5-2 times of the theoretical quantity of sodium sulfite should be used. In this experiment, 1.75 times of the theoretical quantity was used; thus 97 mg of sodium sulfite was added to 1 L of solution where 7 mg/L of oxygen initially existed. Cobaltous chloride was added as catalyst as it fastens the reaction even at very low concentration [52]. Hence, 0.5 ml of 1% solution of cobaltous chloride was added to every 1 L of cassava solution. Main experiments were then conducted by manipulating process variables at different combination: (1) aeration rate at 0.6 L/min and 1.2 L/min (2) impeller speed at 100 rpm, 300 rpm and 500 rpm (3) temperature at 37 °C and 45 °C. During aeration, air was sparged into the solutions until the saturation DO concentration was reached. Dissolved oxygen was recorded as a function of time. Obtained experimental data of DO are in the percentage of DO, pO_2, which is defined as percentage of saturation DO concentration. In total, there were 32 sets of experiments and each set was performed three times. Therefore, all experimental data used in the modeling study were the average value of these replications. Samples of the average value of the experimental data can be seen in Table 3.

4. Mass Transfer Studies and Determination of K_La

Oxygen transfer into cassava solution was described using the following mass balance model [26-28,32,53]:

$$dC/dt = K_La\,(C^* - C) \qquad (2)$$

where dC/dt is the rate of oxygen accumulated in the solution, K_La is the volumetric mass transfer coefficient and C^* is the saturation concentration of oxygen in the solution. K_La was evaluated by trial-and-error by minimizing error between predicted DO and experimental DO concentrations. A tolerance of 0.00001 was used as a criterion of the calculation. A flow chart of the trial-and-error algo-
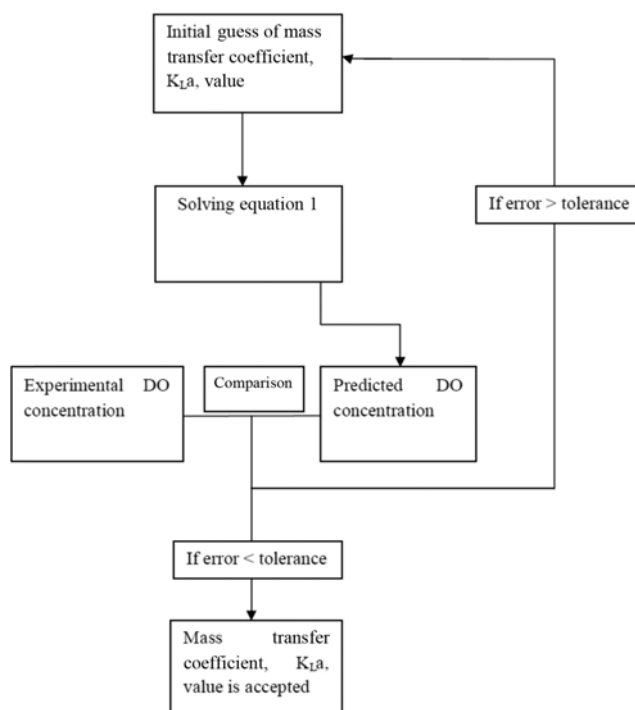
Fig. 2. Algorithm of the trial-and-error method.

rithm is shown in Fig. 2.

RESULTS AND DISCUSSION

1. Saturation DO Concentration

The saturation DO concentrations for all experimental run are in Table 3. The experiments were carried out at different operating

parameters: concentration of the starch in the solution, aerating rate, stirring rate and temperature. Based on this table, it is evident that the saturation DO concentrations are influenced by concentration of the starch in the solution and temperature of the system. An increase of cassava starch concentration results in an increase of viscosity, and this will lead to higher mass transfer resistance since more viscous solution has less interaction between gas and liquid. Consequently, the maximum amount of oxygen transferred to the solution will also be less as indicated by lower saturation DO concentration. Table 3 also shows that the saturation DO concentration decreases with increasing solution temperature. These findings are consistent with the oxygen transfer in water studied by Chern et al. [54]. On the other hand, it is obvious that aeration and stirring rates have no impact on the saturation concentration. Their effects may be in shortening the time to arrive at the saturation points. Higher aeration and stirring rate create better turbulence and mixing, which sets the oxygen transfer.

2. Modeling Accuracy

To confirm the accuracy of the model (Eq. (1)) and validity of the obtained K_La values, experimental data and simulated data at different operating conditions were compared. Simulated data were generated by solving Eq. (1) using optimal values of K_La. Fig. 3 shows samples of these comparisons. These figures indicate that simulated data agree with the experimental ones. Deviations between

experimental and simulated data were found to have an average of 5.33%, which further indicates that the model is well-fitted and the obtained K_La values are optimal and accurate. Values of K_La and average percentage errors at different operating conditions are in Table 4. These values were compared with the K_La values for oxygen transfer to water from other studies [35], as shown in Table 5. These comparisons indicate that the obtained K_La values from this study are comparable and have ranges that agree with the ones from other works. Table 4 also reveals that the values of K_La are very sensitive to operating conditions. The effects of different operating conditions on K_La are discussed in detail in the following sections.

3. Effect of Stirring Rate on K_La

The effects of various stirring rates on the K_La values were examined at the speeds of 100 rpm, 300 rpm and 500 rpm at constant working volume of 1 L, aeration rate of 0.6 L/min, temperature of 37 °C and pH of 7. From Fig. 4, K_La increases linearly with an increase in the stirring rate. This effect may be attributed to the better gas-liquid interfacial area for mass transfer due to the rapid breakage of the gas bubbles into smaller sizes caused by the higher stirring rate. When more agitation is introduced into the system, the interactions between the liquid and gas are enhanced. This eventually increases effective oxygen transfer area and the transfer of oxygen from moving bubbles to the stationary bulk liquid, resulting in better transfer of oxygen into the solution. For these reasons, few research-
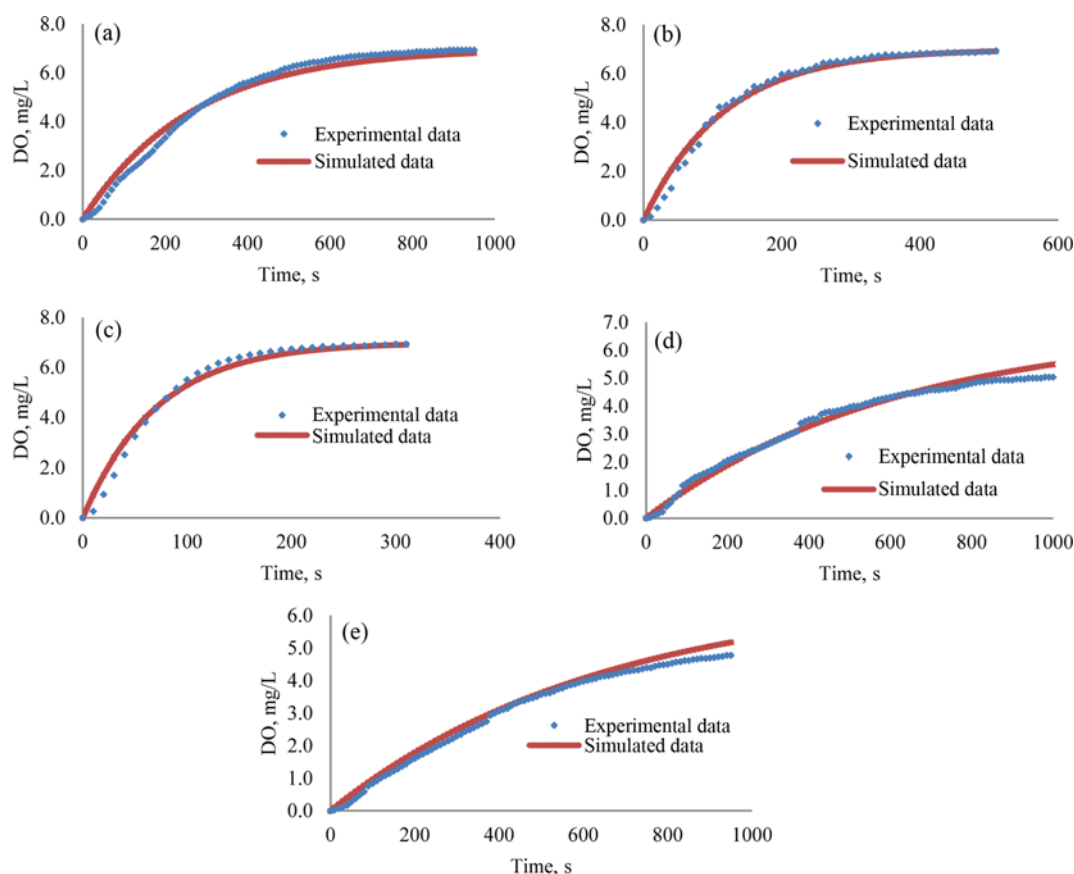
Fig. 3. Comparison between experimental and simulated data at different operating conditions.
(a) SR=100 rpm, T=37 °C, AR=0.6 L/min and CS=0%. (b) SR=300 rpm, T=37 °C, AR=0.6 L/min and CS=0%. (c) SR=500 rpm, T=37 °C, AR=0.6 L/min and CS=0%. (d) SR=100 rpm, T=37 °C, AR=0.6 L/min and CS=5%. (e) SR=100 rpm, T=37 °C, AR=0.6 L/min and CS=10%.

Table 4. Values of $K_L a$ and average percentage errors at different operating conditions

Concentration, %	Temperature, °C	Aeration rate, L/min	Stirring rate, rpm	$K_L a$, min^{-1}	Average percentage error of experimental vs simulated data of oxygen concentration, %
0	37	0.6	100	0.0032958	3.44
			300	0.00868	1.90
			500	0.014052	2.53
		1.2	300	0.013581	1.52
	45	0.6	100	0.0048303	3.92
			300	0.009272	5.72
			500	0.018708	6.58
		1.2	300	0.0092711	5.72
5	37	0.6	100	0.0016355	5.19
			300	0.0022504	5.44
			500	0.0038588	8.01
		1.2	300	0.0025762	5.14
	45	0.6	100	0.0047797	7.75
			300	0.0072422	3.24
			500	0.0086028	5.23
		1.2	300	0.0075009	9.98
10	37	0.6	100	0.0015528	6.06
			300	0.0022753	4.89
			500	0.0035631	4.88
		1.2	300	0.0028231	3.77
	45	0.6	100	0.0028974	7.23
			300	0.0055675	6.11
			500	0.0083131	3.85
		1.2	300	0.012888	5.38
15	37	0.6	100	0.0013869	4.83
			300	0.002319	5.05
			500	0.0034068	3.75
		1.2	300	0.0029925	6.09
	45	0.6	100	0.0029217	12.26
			300	0.0064763	7.56
			500	0.0072379	3.27
		1.2	300	0.0059376	4.35
Average					5.33

Table 5. Comparisons of obtained values of $K_L a$ with the values from the literatures

System	T, °C	Aeration rate, L/min	Stirring rate, rpm	$K_L a$, min^{-1}	Reference
Water	15.5-26.5	1.2-46.02	N/A	0.0064-1.002	[35]
Water	25	1	100	0.1505	[30]
Water	37-45	0.6-1.2	100-500	0.003-0.019	This study
Water+Cassava starch (5%)	38-45	0.6-1.3	100-500	0.0016-0.0086	This study
Water+Cassava starch (10%)	39-45	0.6-1.4	100-500	0.0015-0.0083	This study
Water+Cassava starch (15%)	40-45	0.6-1.5	100-500	0.0013-0.0072	This study

ers [26,27,33] have borrowed the correlations of stirring rate (N) and $K_L a$ from the system of gas absorption in a stirred tank to be implemented in the aeration of water. This correlation is $K_L a = A.N.D^{\alpha 1, \alpha 2} \cdot [V_s]^{\beta}$, where A is constant, $\alpha 1$, $\alpha 2$ and β are exponents, V_s is superficial gas velocity and D is the diameter of the impeller. This further justifies that higher $K_L a$ can be achieved by increasing the stirring rate.

4. Effect of Aeration Rate on $K_L a$

The experiments of varying the gas flow rate were performed to investigate the effect of aeration rate on $K_L a$. Observations were made at the aeration rate of 0.6 L/min and 1.2 L/min at constant working volume of 1 L, stirring rate of 300 rpm, temperature of 37 °C
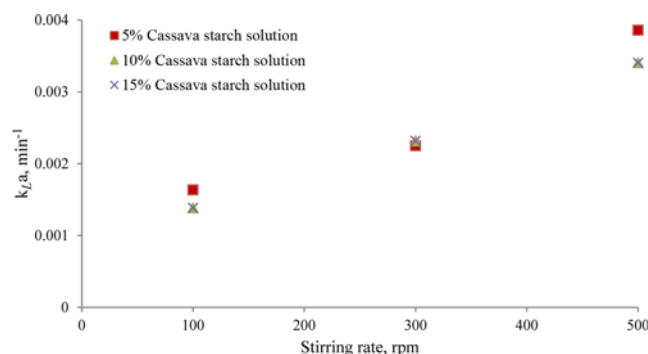
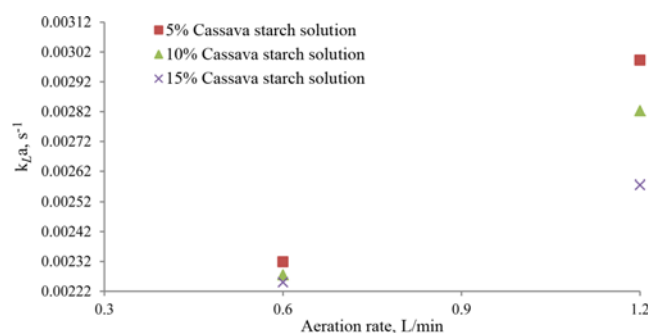**Fig. 4. Effect of stirring rate on the K_La values.**

Fig. 5. Effect of aeration rate on the K_La values.

and pH of 7. Fig. 5 indicates that K_La increases proportionally with increasing diffused airflow rate at given concentrations of cassava starch. This phenomenon is logical since changing the flow rate of gas will also change the fractional gas hold up, create liquid flow turbulence and thus enhance the gas-liquid interactions and areas. Therefore, higher mass transfer rate is observed when the aeration rate is increasing. This conclusion agrees well with the correlation of $K_La = A.N.D^{\alpha 1, \alpha 2} \cdot [V_s]^\beta$. Different values of β exist, as summarized by Özbek et al. [27].

5. Effect of Cassava Starch Concentration on K_La

Fig. 6 shows the effect of starch concentrations on K_La. The data were obtained from the experiments of varying starch concentrations of 5%, 10% and 15% at constant working volume of 1 L, aeration rate of 0.6 L/min, temperature of 37 °C and pH of 7. From Fig. 6 the K_La value is smaller when the concentration of starch is higher.
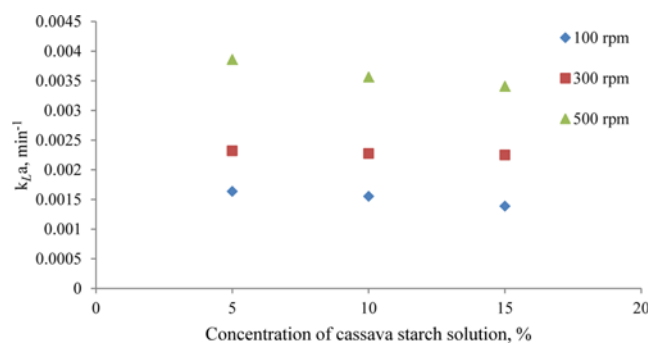

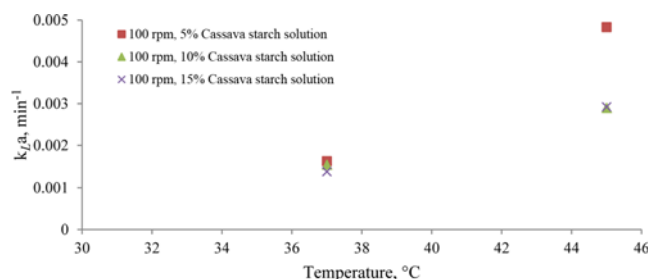**Fig. 6. Effect of concentration of the starch solution on the K_La values.**

Fig. 7. Effect of temperature on the K_La values.

Historically, it is believed that K_La is proportional to the diffusion coefficient of oxygen due to the existence of stationary films in the liquid phase at the interface of the bubbles [30]. Oxygen diffusion coefficients had been found to decrease with the increase of concentrations of substances in water [34]. Therefore, it is logical that lower K_La is expected for higher concentration of starch in the solution. Moreover, with the increase of concentration, the viscosity of the solution will be higher, and this leads to a decrease in the degree of liquid flow turbulence and an increase in the mass transfer resistances, which hereby decreases mass transport intensity. More viscous solution tends to reduce the interactions between gas and liquid, and consequently it reduces area and coefficient of mass transfer.

6. Effect of Temperature on K_La

The effect of temperature on K_La was investigated through experiments of varying temperatures of 37 °C and 45 °C at constant working volume of 1 L, aeration rate of 0.6 L/min, stirrer rate of 100 rpm and pH of 7. From Fig. 7 shows that higher temperature will result in higher K_La. The reason for this phenomenon may be explained in the following. As discussed in section 5, K_La is proportional to the oxygen diffusion coefficient. Generally, the diffusion coefficient is a function of temperature, and it increases with increasing temperature as molecules move more rapidly [55]. Consequently, higher K_La is evident at higher temperature. This finding is also consistent with the conclusions from Chern et al. [35], Downing et al. [56], Elmore et al. [57], Metzger et al. [58], Bewtra et al. [59] and Lakin et al. [60] for a water only system. At higher temperature, the solubility of oxygen is also lower (as indicated by Table 3), and this leads to a smaller driving force (C^*-C). However, with the increasing temperature the solution viscosity is lower and the diffusion coefficient is higher. Therefore, these combined effects result in higher K_La to offset smaller driving force as indicated also by Vogelaar et al. [28] in their experiments for a water system.

CONCLUSIONS

The volumetric mass transfer coefficients, K_La, have been estimated for oxygen transfer to cassava starch solution in an aerated, stirred bioreactor. Analysis and evaluation of the experimental data indicates that K_La values are greatly influenced by process variables such as stirring rate, aeration rate, concentration of the cassava starch and temperature. It was found that the higher the stirring rate, aeration rate and temperature applied in the system, the higher K_La that will be obtained. Meanwhile, lower K_La is expected when concentration of cassava starch in the solution is increasing. From the experimental results, it was also obvious that saturation DO con-

centration is affected by concentration of the starch and temperature. However, it is neutral toward stirring and aeration rates.

NOMENCLATURE

AR : aeration rate [L/min]
C : concentration of oxygen in the solution at any time [mg/L]
C^* : saturation concentration of oxygen in the solution [mg/L]
CCD : calcium chloride dihydrate
CMC : carboxy methyl cellulose
CS : concentration of starch [% (g/L)]
DHP : dipotassium hydrogen
DO : dissolved oxygen [mg/L]
k_L : liquid side mass transfer coefficient
$K_L a$: volumetric mass transfer coefficient [1/min]
MSH : magnesium sulphate heptahydrate
PDP : potassium dihydrogen phosphate
PEG : polyethyleneglycol
pO_2 : percentage of saturation DO concentration [%]
SR : stirring rate [rpm]
T : temperature [°C]

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