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Evaluating the Use of Airlift Pumps for Bioreactor Applications

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Abstract – In this study, preliminary experiments were performed in order to evaluate the performance of bioreactor using airlift pump. A patented airlift technology is integrated in a bioreactor and compared to a stirred tank bioreactor. Oxygen mass transfer and water salinity were used to characterize the mixing effectiveness. For the same aeration rate, power consumption is used to compare both conventional and airlift systems at different operating conditions. Also, airlift pump found to create a larger number of bubbles and consequently larger total surface area that allow for more interfacial oxygen transport. The results show a great potential of airlift use in bioreactors to achieve better bioreactor performance with a huge power reduction.

1. Introduction

The industrial aerobic processes carried out in aqueous viscous broths are considered to follow a non-Newtonian behaviour because these broths usually contain salts and organic substances including microbes [1]. In these processes, oxygen is an important nutrient used by these microbes for growth and metabolic processes. Hence, oxygen transfer to these broths is crucial and the lack of required oxygen affects the performance of the process. This makes oxygen transfer rate (OTR) into the broth an important parameter for efficient biological processes. Due to the low solubility of oxygen in liquid media combined with the depletion of oxygen content due to microbial uptake, reaction could be limited in such processes. The OTR depends on many factors including the aeration rate, gas flow rate, temperature concentration, geometry of tank, etc. [2]. Therefore, these processes are often carried out in bioreactors to control such performance.

Bioreactors are controlled environments to contain any biological process including microbial presence. Currently, there are many types of reactors present in the industry, but the simplest and most popular reactor is the stirred tank reactors. These reactors contain a sparger to distribute gas into the liquid in the form of small bubbles and an agitation system containing impellers that causes an intense mixing of the liquid medium within the tank. The fractional gas hold-up in these reactors is the main parameter that describe the efficiency of gas-liquid contact [3].

With technological advancements in aeration and pumping technology, power consuming stirred tank reactors could possibly be replaced by more efficient systems. One such possibility is the integration of airlift pumps in bioreactors. Airlift technology has been implemented in bioreactors in the past and has proven to be highly efficient. What makes this system attractive is its simplicity of construction, better defined flow patterns [4] and low power requirements [5]. The design of airlift pumps has been known since 1797 when it was introduced by an engineer (Carl Loesher) in a coal mining industry to pump slurries through mine shafts [6]. Airlift pumps are considered as special effect pumps that lifts up liquid or mixture of liquid and solid by utilizing a compressed gas. The injection of air in a submerged pipe causes a lower hydrostatic weight of the gas-liquid mixture relative to its surrounding medium. This causes the mixture to rise up through the pipe. The airlift technology is used in many applications such as underwater mining, seawater sample collection, aquaculture, waste water treatment, etc. [6]. An unintended but positive side effect of airlift pumping is the mass transfer of gas to the liquid medium, which is a desirable trait in aerobic processes.

Currently, the efficient airlift systems are on their way to the markets. One such airlift system for bioreactor application is being developed at the University of Guelph. The main attractiveness of airlift technology in bioreactor processes is the reduction of power consuming components in the conventional systems such as the stirred tank reactors. The new system can possibly replace the stirrer and sparger with a single component. In most industrial settings, compressed air is a cheap and freely available commodity compared to power consuming motors. However, the reduction in power consumption in these systems should not interfere with the general working of these reactors. Hence, this initial study will determine if the new system will meet the criteria of the older systems. Therefore, the main goal of this work is to study the effectiveness of these injection systems integrated into bioreactor processes. Since, the effectiveness of bioreactors vary between different processes however, the main parameters that will be used for comparison will be oxygen transfer rate, mixing rate and power consumption. In this paper, the patented airlift pump developed by Ahmed et al.[7] will be used to carry out the objectives of this study.

1.1. Oxygen Transfer Rate (OTR)

In stirred tank bioreactors, the sparger provides oxygen to the system by injecting air bubbles that rises in the liquid medium. The oxygen then transfers to the liquid medium from the air bubble through gas-liquid interface. There are multiple theories on gas-liquid mass transfer and in all the cases, the driving potential of mass transfer is proportional to the difference between actual conditions and conditions at equilibrium [8]. The most widely used theory is the two film model which describes the flux through each film as the product of driving force by the mass transfer coefficient [1].

$$J^0 = k_G\left(p_g - p_i\right) = k_L(C_i - C_L) \tag{1}$$

where J^0 is the molar flux of oxygen ($mol.m^{-2}s^{-1}$) through the gas-liquid interface. The subscripts L and G stand for liquid and gas phase. k is the local mass transfer coefficient, p is the partial pressure in the gas bubble and C is the concentration of oxygen. Index 'i' refers to the values at gas-liquid interface. However, this is hard to measure and so, the flux equation is rewritten in terms of equilibrium values (index *) and K represents the overall mass transfer coefficient in this equation [1].

$$J^0 = K_G\left(p_g - p^*\right) = K_L(C^* - C_L) \tag{2}$$

Applying Henry's Law ($p^*=H C^*$ and combining the equations (1 and 2), the following relationship is obtained

$$\frac{1}{K_L} = \frac{1}{Hk_G} + \frac{1}{k_L} \tag{3}$$

Since the solubility of oxygen is low in liquids, the liquid side of the interface provides the greatest resistance for mass transfer through a gas-liquid interface. Hence, common practice is to neglect the gas phase resistance, which results in a local liquid mass transfer coefficient being the same as the overall mass transfer coefficient ($K_L=k_L$). Therefore, Equation (1) reduces to the following:

$$\frac{d(DO)}{dt} = k_L a(DO^* - DO) \tag{4}$$

After integration and linearization this equation can be rearranged to obtain k_L as follows:

$$\ln\frac{\mathrm{DO}^* - DO}{DO^* - DO_0} = k_L a(t - t_0) \tag{5}$$

In bioreactors, the liquid is aerated as sustenance to the microbial presence in the tank. A Mass balance for the dissolved oxygen in any bioreactor can be obtained. For a well-mixed liquid phase, the mass balance equation can be established as discussed by Garcia-Ochoa et al. [9]:

$$\frac{dC}{dt} = OTR - OUR \tag{6}$$

$$\frac{dC}{dt} = K_L a(C^* - C) - q_{O2}C_x \tag{7}$$

where OTR is the Oxygen Transfer Rate and OUR is the Oxygen Uptake Rate by the microbes.

2. Experimental Work

Comparison of the two systems required experimental simulation of the systems. The experimental simulation required setup design that carefully considers the components and parameters of the systems. A stirred tank bioreactor was obtained for the purpose of this project. To simplify the process, water is used as the bioreactor content due to easy availability. The reactor is a 20 litter cylindrical glass vessel that is hung from the lid with the help of a jacket (Fig.1a). The reactor came with the structure that holds the lid in place. The agitator motor is bolted to the structure above the lid as shown in Figure 2a. The reactor had a 2 impeller agitator and a 1x1 m (diameter x height) sparger. The airline of the sparger is a metal pneumatic pipe that enters the bioreactor through its lid. Compressed air is provided to the sparger and airlift pump through a central compressed line. The exact size of the bioreactor is shown in the Fig. 2a.

In order to compare results, the patented airlift pump designed by Ahmed et al. [7] is utilized. The airlift pump was designed to fit the bioreactor system. Careful considerations were taken to add minimal changes to the system already in place. The single inlet to the airlift pump is introduced into a chamber that contains multiple outlets into the pipe. The parameters for the injection system designed to fit the size of the airlift for the bioreactor according to the specifications in [7]. Two experiments were performed as part of these preliminary tests and baseline comparison between the conventional system and the modified reactor using airlift in order to compare the mass transfer coefficient values. The equipment used for the setup and performing these measurements include the bioreactor, a nitrogen tank, a power meter, a rotameter, pneumatic tubing, dissolved oxygen meter and a salinity meter.

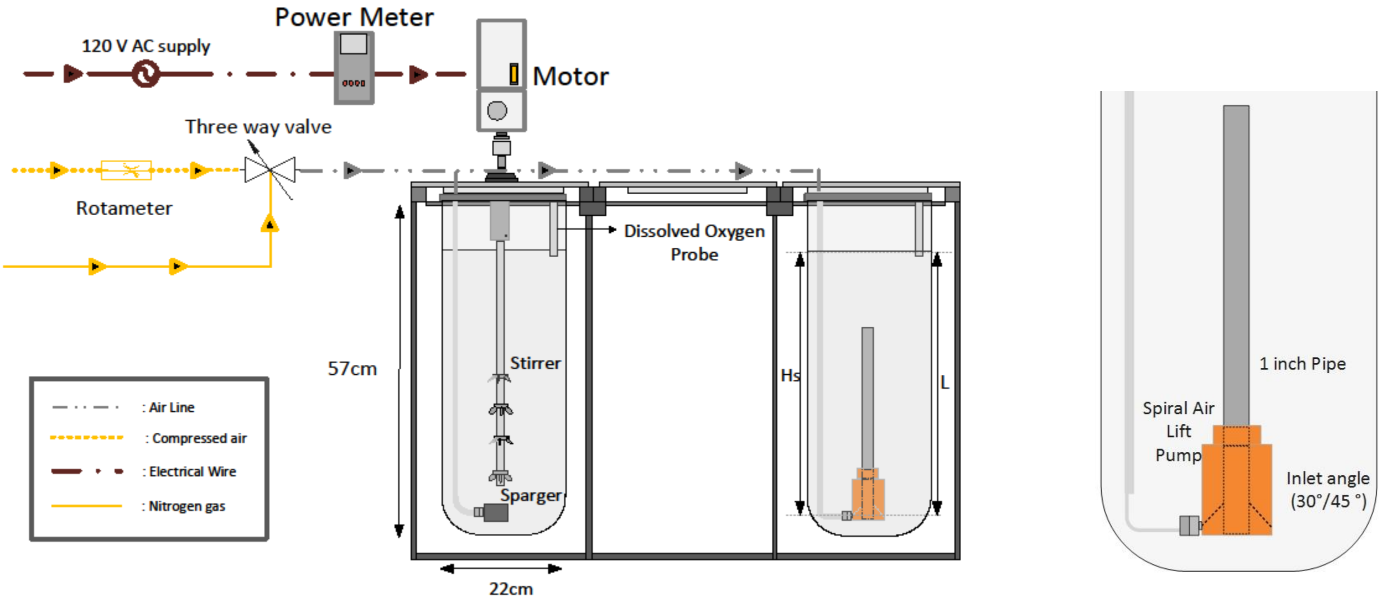
(a) Conventional system setup (b) Detailed view of the reactor

Fig. 1: Sparger-stirrer bioreactor system.

2.1. Mass Transfer Experiment

The experiments were set up so that the dissolved oxygen content is the same at the start of every run. The bioreactors have one pneumatic inlet that contains a three-way valve. This valve can be adjusted to sparge the reactor with the desired gas. The inlets of the three-way valve are compressed nitrogen and compressed air. Initially, the water in the reactor is sparged with nitrogen gas to lower the dissolved oxygen content in water (DO) to 1mg/L. The water was then sparged with air at constant flow rates to increase the DO to 8.75 mg/L. The experiment was conducted at approximately 21^{o}C. The DO was measured by a dissolved oxygen meter that was connected directly to a computer. Data was collected by LABVIEW every 10 seconds.

Experiments were performed in two 20L glass bioreactor tanks; one tank with airlift and the other, the conventional system. The tanks are filled with 18.5 L of water. Nitrogen is sparged through both the airlift and the conventional system to reduce the dissolved oxygen content to 1 mg/L. The motor speed for the impeller is kept constant and data is collected for dissolved oxygen while sparging both systems with air at varied flow rates. The process of sparging air from 1mg/L is repeated for various motor speeds. The motor speeds used in the preliminary testing are 300, 500 and 800 rpm while the flow rates used were 12.5, 18 and 24L/min. The power consumed by the motor is simultaneously measured.



(a) Overall set up for the experiments

(b) Airlift pump

Fig. 2: Set up.

2.2. Mixing Experiment

In any aerobic process, the broth needs to mix for even distribution of microbial population as well as even aeration throughout the tank. The mixing between the two tanks were compared in this experiment using a salinity test. The same amount of salt was added to both the tanks (850g) and using a salinity meter, the percentage salinity was measured manually for every 10 seconds.

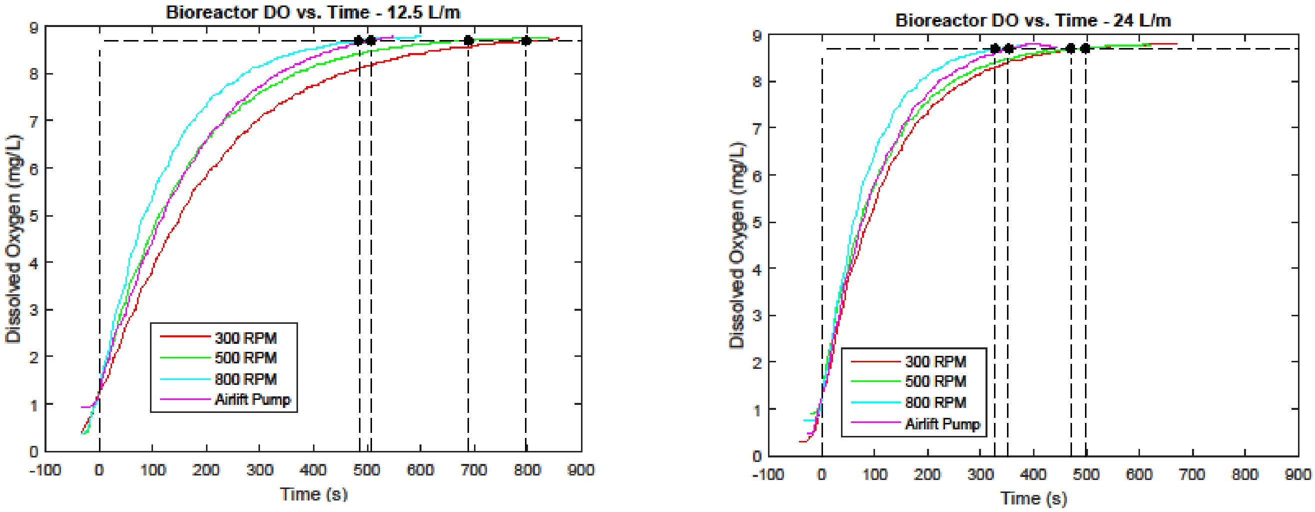
3. Results and Discussion

3.1. Mass Transfer Experiment

The preliminary results found to be consistent for each run of the experiment. These results show a direct relationship between air flow rate and the oxygen transfer rate. This is expected since a higher flow rate creates a larger number of bubbles and larger total surface area that allow for more interfacial transport. This is mainly due to the larger contact area between gas and liquid phases which leads to a better oxygen transfer rate. The data is summarized in Table 1 in the form of the time taken for dissolved oxygen to rise form 1 mg/L to 8.75 mg/L at a temperature of 21 °C for different system operating conditions. According to Henry's law, the saturation point of dissolved oxygen in water at these conditions is 8.90 mg/L. From the table, it is clear that the slowest system is 300 RPM at 12.5 L/min (lowest motor speed and lowest air flow rate) and the fastest system is the fastest motor speed and highest flow rate. The airlift system found to have relatively high effectiveness in oxygen transfer. However, 800 RPM has a better effectiveness than the airlift system. This is justifiable as the power required to run this motor at 800 RPM is approximately 58 W while the power required by the airlift is minimal and much lower than the motor power input. This is explained when power consumption is discussed.

Table 1: Time taken for dissolved oxygen to rise form 1 mg/L to 8.75 mg/L.

	Air Flow Rate			
		12.5 L/min	18 L/min	24 L/min
System Condition	300 RPM	797.27s	652.56s	498.99s
	500 RPM	688.89s	543.20s	469.53s
	Airlift	506.16s	397.36s	352.32s
	800 RPM	485.13s	356.22s	326.31s



(a) 12.5 L/min air flow (b) 24 L/min

Fig. 3: Results showing dissolved Oxygen vs. Time for 800RPM motor speed.

The trend shown in Figs. 3a and 3b founds to be consistent with equation 4. As the dissolved oxygen content approaches equilibrium in water, the right hand side of the equation starts to decrease. This causes the oxygen transfer rate to reduce drastically as concentration approaches equilibrium. Results show that the air lift system offers a relative good oxygen transfer rate in approximately the same time period. The oxygen transfer rate is consistently higher than the conventional system while running the motor at 300RPM and 500 RPM. Also, the results show direct relationship between the impeller speed and oxygen transfer rate. In stirred tank reactors, the impeller plays a crucial part in the oxygen transfer rate due to the different bubble distribution in both cases. Fig. 4 illustrates the bubble distribution during the mixing process in a bioreactor. The relationship between stirrer speed and volumetric mass transfer coefficient suggested agree with the observation of Åkesson and Hagander [10]. The relationship between stirrer speed and volumetric oxygen transfer coefficient that has been suggested in [10] under reasonable stirrer speeds as:

$$K_L a(N) = \alpha(N - N_0) \tag{8}$$

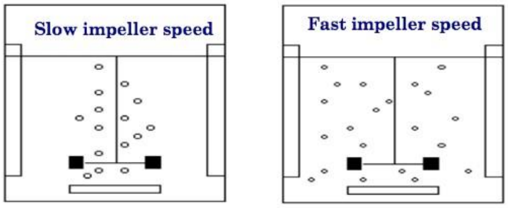
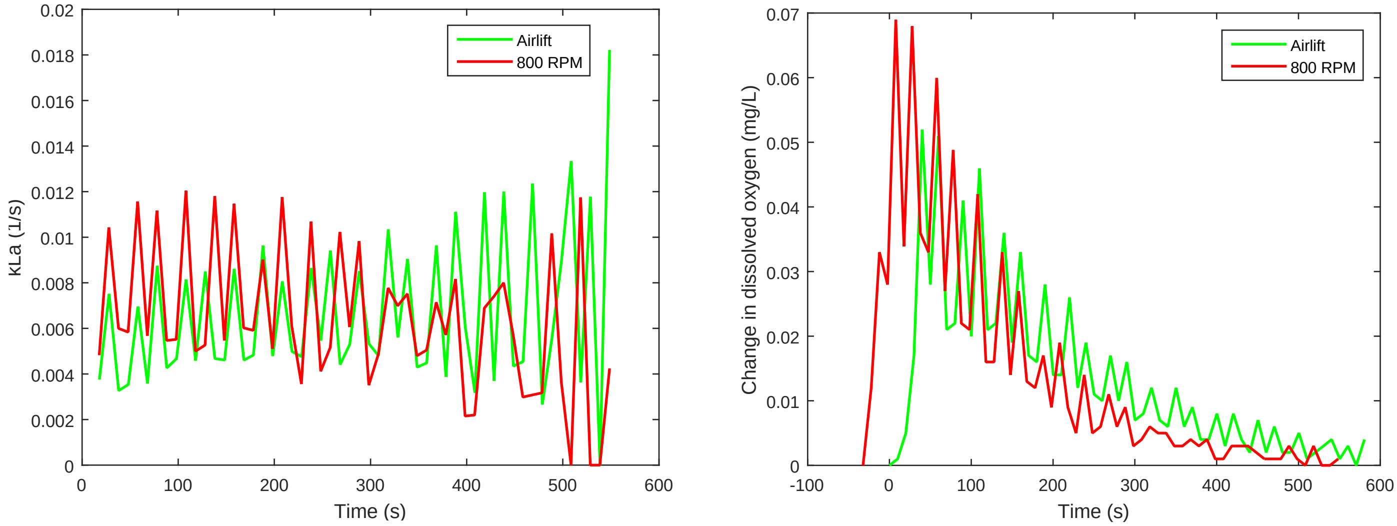


Fig. 4: Effect of stirrer speed in mixing and aeration.

The rate of change in the dissolved oxygen was calculated from the "dissolved oxygen vs. time" shown in Figs. 3a and 3b. Moreover, Fig. 5 gives a better idea of how the airlift is compared with the conventional system. In this figure, the performance of the conventional bioreactor operating at 800 RPM and the bioreactor utilizing airlift system. From the data for 300 RPM and 500 RPM, it can be noted that the airlift consistently has a higher dissolved oxygen rate over the 300RPM system. Initially the 500 RPM system appears to have a higher dissolved oxygen rate than the airlift, however as the time elapses the airlift shows a better rate. As expected, 800RPM has the highest dissolved oxygen rate. Fig. 5b shows that the airlift has a lower rate of change initially but has a higher rate of change towards the end. This is expected since the 800 RPM system is reaching equilibrium faster than the airlift and as distance from equilibrium decreases, the oxygen transfer decreases as well. From Fig. 5a, it is observed that k_La (Volumetric mass transfer coefficient) oscillates through a long time range. The average values are given in Table 2. These values show a higher mean k_La value for the airlift than the 800 RPM system. This is not consistent with the rest of the results in this report and needs to be considered in future tests.



(a) Volumetric mass flow rate as a function of time (b) Rate of change of dissolved oxygen with time

Figure 5: Figures showing a comparison of the airlift system with the 800-RPM system.

Table 2: Mean k_{La} values for each system. (Results obtained from Fig. 5a).

Setup	$k_L a$
300 RPM – Conventional System	0.00407
500 RPM – Conventional System	0.00427
800 RPM – Conventional System	0.00607
Airlift System	0.00662

3.2. Mixing Experiment

The preliminary results of airlift mixing shows consistent results from that of the conventional system (Fig. 6). It should be noted that the points in the graph that seem to be outliers are isolated points of high salinity in the bioreactor. This is also indicate that the tank is not completely mixed yet. Hence, reaching a consistent steady state value is presumed to be "well mixed". The steady state is reached at approximately 200s in both systems. This is when the system starts to reach steady state and achieve consistent results.

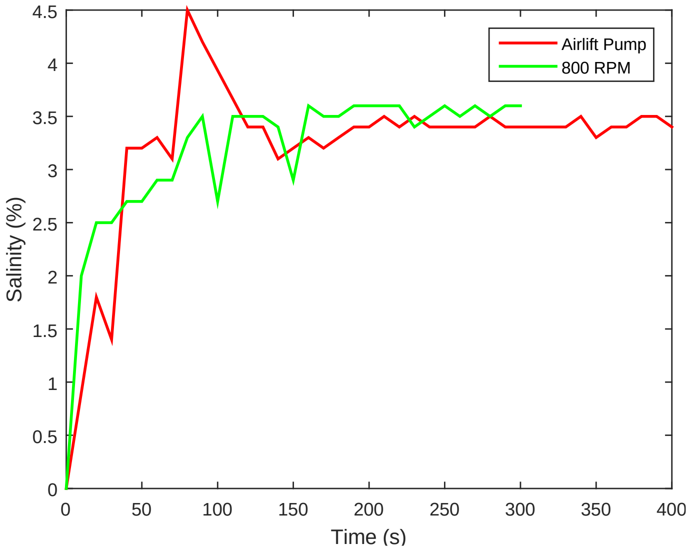


Fig. 6: Salinity as a function of time.

3.3. Power Consumption

In these experiments, motors found to have high power consumption compared to the power needed for the compressed air. Results from preliminary experiments (using a power meter) are listed in the Table 3a. The power required to compress the air can be calculated using the isoethermal expansion of the air as suggested by Ahmed et al. [7].

$$Power = P_a Q_a \ln(\frac{P_{in}}{P_a}) \tag{9}$$

where P_a and P_{in} represents the atmospheric pressure and the injection pressure respectively while Q_a represents the volumetric air flow rate into the injector. The injection site for the airlift and sparger are located at a depth of 0.47m. The total volume of water in the talk is 18.5L and hence, the power can be calculated calculated using equation 9.

Assuming that the sparger and airlift has the same resistance at injection, it can be estimated that both the sparger and airlift consume the same amount of power (Table 3b). Hence, the power difference between the conventional system and the air lift system with the same inlet air flow rate will be the power consumed by the motor in the conventional system. To give an idea of energy savings, if a biological process is run for 24 hours at the experimental scale at 800RPM and 24L/min air flow rates, the energy savings by the air lift system will be 1.32 kWh. For industrial scale bioreactors, considerable energy savings could be expected.

Table 3: Power consumption data.

(a) Power consumption under different motor speed

Motor Speed	Power (W)
300 RPM	51
500 RPM	52
800 RPM	55

(b) Power required to compress air

Airflow rate (L/min)	Power (W)
12.5	0.94
18	1.35
24	1.80

4. Conclusion

In this preliminary study, the mass transfer rate between air and water, agitation effectiveness and power consumption are used to evaluate the use of airlift pump for bioreactor applications. The results show a great possibility of integrating airlift in bioreactors to achieve similar or better performance with a huge reduction in power consumption in the order of 50 times. Airlift pump found to create a larger number of bubbles and consequently larger total surface area that allow for more interfacial oxygen transport. In general, the air lift system found to be an energy efficient option when compared to conventional systems.

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