Improvement of oxygen transfer efficiency in the activated sludge process

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Abstract. Sequential batch reactor (SBR) is a feasible and economically attractive alternative to continuous activated sludge process to remove pollutants (dynamics and flexibility). Most of the power consumption is consumed by the aeration system to aid the removal of contaminants. Therefore, an optimal aeration system must be proposed to ensure cost-effective and efficient treatment of wastewater. The objective of this study is to evaluate the effect of air flow rate on the oxygen transfer efficiency of the SBR reactor. Based on the results, the removal efficiency of COD and AN at an air flow rate of 7.0 LPM (5.0 mg/L) were slightly higher than the air flow rate of 5.0 LPM (4.0 mg/L). However, the improvement is not exceptional. Excessive DO level and aeration should be avoided to achieve cost-effective yet efficient removal of pollutants.

1. Introduction
The change in socio-economic due to industrialization causes several major impacts to the environment and one of the notable impacts is the generation of industrial wastewater which must go through treatment before being discharged into the environment. The poultry processing industries are growing rapidly to support domestic food supply in the national arena. Poultry processing plants and slaughterhouse are one of the most common industrial plants in Malaysia. Poultry processing industry are well known as high strength wastewater consist of high concentration of biologically contaminants. The blood from poultry processing industry is quantified to have high impact on wastewater characteristic besides its other biological wastes such as fat, feather and other organic material. Researcher conducted a research on the effect of chicken blood and its component on wastewater characteristics shown a significant effect on sewerage treatment plan and how the sewerage authorities come to impose surcharge to the poultry industry [1].

The concept of sequential batch reactor (SBR) is an attractive alternative to conventional continuous activated sludge process to achieve the removal of various contaminants due to its practicable and economically attractive. The dynamics and flexibility of SBR ensure there are adequate potential for future expansion and operational configurations with a minimal cost [2-4]. The employment of SBR has been proved to be an efficient wastewater treatment process due to its simplicity and high removal efficiency of organic compounds and solids [5]. The efficiency of SBR system is depending on the biochemical process in Mix Liquors Suspended Solid which is depending on the oxygen transfer from the aeration system. Oxygen transfer from gas phase to liquid phase that
occurs in the aeration tank plays an essential role in aerobic biological treatment or else the effectiveness of biological degradation will be jeopardized. Oxygen transfer process consumes the largest composition of energy in activated sludge processes (ASPs) [6]. The efficiency of aeration is correlated to the characteristics of sludge – mixed liquor suspended solids (MLSS) and other operating conditions such as air flow rate, dissolved oxygen concentrations, etc. [2].

The oxygen transfer can be determined either by dynamic method (non-steady state) or The Off-Gas Method. The Dynamic Method has been widely used where the change of oxygen concentration is measured although the saturation in liquid is reached [7]. The oxygen transfer coefficient \(k_{l,a}\) is an important parameter to evaluate the gas-liquid in reactor’s performance and this value is linearly increased proportional to superficial gas velocity [8,9].

There many technique to investigate the oxygen transfer process in reactor and it can be range from direct dispersion of air into water either by strip diffuser, modified air lift, fine bubble column reactor, orifis and etc [8,10,11]. Some researcher had shown that the oxygen transfer coefficient is directly proportional to an interfacial surface contact area and oxygen deficient but adversely to liquid film thickness in their research in aeration reactor using modified small Parchall Flume [10]. Some literature also indicates that high concentration of dissolve oxygen would enable a higher active biomass, increase deep released oxygen in the flox mass as well as volume of inner aerobic section. The research also shown that the increasing of dissolve oxygen (from 0.5 to 4.5 mg/L) had resulted a reduction of sludge production up to 25% [3].

Due to the concerns of high energy demand and seeking of optimum aeration intensity, present study was conducted to improve the efficiency of oxygen transfer in activated sludge process by strip diffuser with different inlet air flow rate on SBR reactor and to evaluate the performance of each oxygen transfer to SBR performance in terms of pollutant removal.

2. Materials and method

2.1. Sample preparation and reactor setup

Raw wastewater and activated sludge as microbial culture seed from poultry processing industry (Advance Chicken Processing (M), Jejawi, Perlis) were collected in batches and stored in refrigerator in constant temperature. The poultry wastewater was in high concentration of biologically contaminates such as blood, fat, feather and other organic materials. A laboratory-scale Sequence Batch Reactor (SBR) with capacity of 13L (GT 3001 R) rectangular Perspex tank; with working volume of 8 L consist of 4.5 L of raw poultry processing wastewater and 3.5 L of activated sludge were used in this experiment. The reactor was equipped with a 10.5” of strip air diffuser at the bottom of reactor floor and connected to 3 air pump (Regent 9500, Regent 7500, Regent-JIT 666A) with combined air flow up to 7L/min.

Basically, the operation of SBR consists of 5 phases which started from Fill, React, Settle, Decant and Idle Stage. In each cycle, 3 L of fresh wastewater was feed into the reactor during Fill Stage. At this moment, initial readings of Dissolve Oxygen (DO) were taken using DO Meter (YSI 5000). The air diffuser of 3.5 L/min was then operated at React Stage for aeration up to 17.5 Hours before its stop for 2 Hours in Settle Stage where a volume of 3 L of supernatant/treated effluent will be discharged in the Decant Stage before it continued to reach Idle Stage for 1.5 Hours each. Feeding of influent and discharge of effluent were performed by using peristaltic pump (BL 100H, NATONGPUMP). The SBR’s operation were controlled using 24-hour programmed electrical timer (ES-24HT, Eurosafe). The D.O readings were collected at all stages where the main focus was during React Stage in order to determine the oxygen transfer coefficient \(k_{l,a}\) by using Dynamic Method based on Unsteady State dissolve oxygen concentration material balance.

After 21 days of acclimatization period (Air Flow Rate of 3.5L/min), the SBR was operated on three stages under different diffuser inlet air flow rate (2.5L/min, 5.0L/min & 7.0L/min) which creates different DO levels to evaluate the effect of air flow rate and the Oxygenation Efficiency (E) on SBR performance. Diffuser inlet air flow rate was variated using gas flow meter (LZQ-5).
2.2. Oxygen Uptake Rate measurement

The oxygen uptake rate was determined by taking the dissolved oxygen reading taken using DO Meter (YSI 5000) during Fill Stage within 1.5 hours period where new raw wastewater was added into the reactor. During this period, the activated sludge that remained during Idle Stage was mixed and stirred using submersible pump. A graph of DO against time was plotted and Oxygen Uptake Rate (OUR) was determined by the slope [12].

The oxygen consumed by microbials in the wastewater during aeration process is also known as Oxygen Uptake Rate or (OUR). The oxygen transfer into wastewater can be determined by overall mass oxygen transfer coefficient, $k_La$ by using the mathematical equation [13]:

$$\left(\frac{dC_L}{dt}\right) = K_La(C^* - C_L) - OUR$$

where $C_L$ is bulk liquid DO level at any time $t$, mg/L & $C^*$ is the constant oxygen saturation concentration.

2.3. Performance monitoring and analysis

The evaluation of oxygen transfer through air diffuser was performed by estimating the Oxygenation Capacity (OC) and Oxygenation Efficiency (E). Rate of oxygen transfer by aerator or known as Oxygenation Capacity is defined as the standard rate of oxygen transfer $dC/dt$ at initial oxygen concentration $C_{L0}= 0$ in standard condition [14].

$$OC = \left(\frac{dC_L}{dt}\right) = K_La(C_s - 0) = K_La \cdot C_s$$

While the Oxygenation Efficiency (E) is defined as the fraction of oxygen transferred into water due to pass one cubic meter of air [14].

$$E (%) = \frac{OC \times \text{Depth liquid in tank (m)}}{\text{Aeration intensity (m$^3$/Hr)}} \times 100\%$$

Performance of oxygen transfer to SBR operational efficiencies was performed by analyzing soluble chemical oxygen demand (sCOD), ammonia nitrogen (NH$_4^+$-N), total suspended solids (TSS) and pH. Microbial culture was monitored as well. Mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), SV$_{30}$ and sludge volume index (SVI) were monitored throughout the study.

$$SVI_{30,ml/g} = \frac{\text{Settled Sludge Volume/Sample Volume, mL/L}}{\text{Suspended Solids Concentration, mg/L}} \times \frac{1000 \text{ mg}}{\text{gram}}$$

3. Results and discussion

3.1. Oxygen transfer performance

In the submerged aerated process in the SBR, the oxygen transfers from the air bubbles diffused from energized pump transfer to the surrounded liquid. In the activated sludge process, oxygen consumed by the microbial to disintegrate all elements in the wastewater into a new cell as well as other biodegradable matter. A graph of $C_L$ against (OUR + $\frac{dC_L}{dx}$) were plotted as shown in Figure 1 for 4 type air flows used in the experiments.
The oxygen transfer coefficient \(k_{L}a\) for 2.5, 3.5, 5.0 and 7.0 L/min airflow rate were shown in Table 1. It is found that the oxygen transfer coefficient measured was higher than domestic and other industries especially pharmaceutical waste. \(k_{L}a\) measured from their experimental result was 0.055 \(-1\) and 0.3975 \(-1\) for airflow of 5 and 10 L/min each by using pharmaceutical waste [13], but some researchers showed a higher value of 33.84 \(-1\) for domestic wastewater [15]. Some researchers setup a flow rate of 3.33L/min with different aeration time and frequency came of to a lower oxygenation efficient range from 0.77% up to 1.50% [16].

**Figure 1.** The result of oxygen transfer coefficient, \(k_{L}a\) in various diffuser air flow rate.

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**Table 1.** The result of oxygen transfer performance of measured actual airflow rate.

| Air Flow Rate (L/min) | Oxygen transfer coefficient, \(k_{L}a\) (Hr\(^{-1}\)) | Oxygen Transfer Capacity of the system, OC (g O\(_2\)/m\(^3\).Hr) | Oxygenation Efficiency (\(E\)), \(E=(OC \times Hr)/I\) |
|-----------------------|--------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------|
| 2.5                   | 0.200                                                  | 1.562                                                         | 20.83%                                            |
| 3.5                   | 0.389                                                  | 3.037                                                         | 28.93%                                            |
| 5.0                   | 0.600                                                  | 4.686                                                         | 31.24%                                            |
| 7.0                   | 0.727                                                  | 5.680                                                         | 27.05%                                            |

It is found that the higher air flow creates higher oxygen transfer coefficient \(k_{L}a\) which provides a good agreement as \(r^2\) shown a significant correlation of 0.9907 and it is consistent with many researchers reporting the same finding in their research [6,17,18]. The deeper the air diffuser submerged into the tank, the longer the bubble pathway to travel up to surface leading to fine bubble diameter expending its’ surface contact area between bubble and the water; thus creates a higher aeration coefficient value [17]. Some researchers showed that the deeper (from 1.5 m to 2.0 m) the aeration diffuser, the higher oxygenation efficiency (from 20% to 50%) [19]. The author has shown that a 150 mm depth diffuser depth has good agreement although the diffuser depth was way deeper that reported by the other researchers.
At the same time, the differential value of oxygen transfer rate, \( k_{L,a} \) also depends on type of diffuser and reactor configuration leads to differential gas holdup, bubble up rise velocity and flow regime [7,8]. Therefore, this experimental results should not be compared directly with others except if those factor have been taken into consideration in experimental setup. The experiment found that the airflow rate range between 5 L/min to 7 L/min provided the best Oxygenation Efficiency as shown in Figure 2 but further experiment needs to be conducted. Therefore, higher air flow rate did not provide an upmost efficiency required in the reactor with respect to oxygenation process although the oxygen transfer showed a parallel increment. The air flow regime is depending on the rate of the air flow from the diffuser supplied from external pump and the diameter of the orifice which were believed to be related closely in the bubble formation process [7]. Therefore, higher air diffused has increased the superficial gas velocity (SGV) a probability to create a heterogeneous regime bubble formation which lead to less oxygenation efficiency and this finding shown a good finding related to oxygen efficiency that decreased in power-law relationship. Some researcher shown there is a strong correlation between Oxygenation Efficiency and bubble hydrodynamics [8]. Therefore, in this experiment, the improvement of oxygen transfer with respect to Oxygenation Efficiency can be shown that the air flow rate can be adjusted to the optimum range of 5L/min to 7L/min.

3.2. Effect of airflow rates on SBR performance

3.2.1. Performance of pollutants removal (sCOD, TSS, NH\(_4^+\)-N) Based on Figure 3, the efficiency of pollutants removal increased with an elevation in air flow rate (increasing operational DO concentration) in the SBR reactor from 2.5 L/min to 7.0 L/min. The removal efficiencies in all three stages were generally reliable which shown a consistent pattern.

![Figure 2. The effect of air flow rate in respect to oxygenation efficiency.](image1)

![Figure 3. The efficiency of pollutant removal during experimental period.](image2)
The SBR reactor shows the highest removal efficiency when operating under air flow rate of 7.0 L/min (DO level of 5.0 mg/L) with sCOD, NH$_4^+$-N and TSS removal efficiency of 85 – 91 %, 64 – 69 % and 84 – 89 % respectively. When operating with DO level of 2.0 mg/L, the SBR reactor demonstrated the lowest efficiency in sCOD, NH$_4^+$-N and TSS removal ranging between 74 – 81 %, 49 – 52 % and 71 – 75% respectively. This finding is consistent with the findings of some previous studies where increased in DO will enhance COD removal [20], NH$_4^+$-N removal [21] and TSS removal [6,21]. Increased in aeration pressure can result in improved COD removal [7]. Higher mixing intensity will be created with increasing diffuser inlet air flow rate. The concentration of NH$_4^+$-N in effluent reduced with increasing DO level [21]. Lower DO level can inhibit the oxidation of NH$_4^+$-N. Higher DO concentration can result in higher bioflocculation efficiency [6].

Although the experiment shows a consistent agreement of higher airflow with higher removal efficiency and higher D.O concentration; but this requires higher energy to be injected into the system which will lead to high energy consumption and Operational Expenditure (OPEX) requirement for a wastewater treatment plant.

3.2.2. Sludge Volume Index (SVI) The SVI of the operation of the SBR reactor during experimental period (Day 1 – 29) are shown in Figure 4.

![Figure 4. Changes of SVI throughout the operation of SBR reactor.](image)

The SVI is a good indicator for abundance of poorly settling microorganism especially the Filamentous microorganism that have a high surface area to volume ratio [10]. From Figure 4, there is a trend in which lower SVI was achieved under higher diffuser inlet air flow rate (7.0 L/min) and oxygen transfer coefficient (k$_L$a) and vice-versa. Lower SVI was recorded with higher DO level particularly in municipal plants. A lower SVI indicates better sludge settleability which encourage improvement of sedimentation or solid and liquid separations. The settleable sludge is dense with good settling ability when the SVI of mixed liquor sample is low [14]. This finding also shows a good agreement with the researcher that found that increasing value of SVI would result in reduction of oxygen transfer coefficient [10].

4. Conclusion

The study shows a prominent effect of diffuser flow rate on the oxygen transfer in the activated sludge in the reactor which leads to the efficiency of the SBR system itself. A positive correlation of air flow rate and oxygen transfer rate was consistent with many researchers which report the same finding on their research. The optimum flow rate for this experiment was found between 5 L/min to 7 L/min as the Oxygenation Efficiency shown a cutoff point between air flow rate and the system capability in Oxygenation Capacity. This element is important for the operation of wastewater treatment plant to operation financial capability in OPEX point of view. Higher removal efficiency of pollution (sCOD, TSS and NH$_4^+$-N) was found correlated well with higher oxygen transfer coefficient (k$_L$a) as well as the
diffuser flow rate (increasing DO level). The SVI shows an improvement with the increase of oxygen transfer coefficient ($k_{La}$) which indicates a better settleability and less suspended solids in the effluent. Finally, the optimum diffuser inlet flow rate provides an optimum pollutant removal, yet it is not the most efficient in term of financial requirement.

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