Impacts of operational conditions on oxygen transfer rate, mixing characteristics and residence time distribution in a pilot scale high rate algal pond

L. A. Pham, J. Laurent, P. Bois and A. Wanko

ABSTRACT

Different combinations of operational parameters including water level, paddle rotational speed and influent flow rate were applied to investigate their impacts on mixing characteristics, residence time distribution and gas transfer rate in a pilot-scale high rate algal pond. In closed condition, the paddle rotational speed had a positive correlation with the Bodenstein number (Bo), water velocity and oxygen volumetric mass transfer coefficient (kLaO2) while increasing water level generated a negative impact on these parameters, although the impact of water level on water linear velocity was small. The amplification effect of water level and paddle rotational speed on the sensitivity of Bo and kLaO2 should be noticed. Moreover, paddle rotational speed had more impact on kLaO2 than on Bo. The study in open condition indicated that effective volume fraction had a positive correlation with inlet flow rate and negative correlation with paddle rotation, while the opposite was observed in the case of Peclet number. The impact of water level variation on these parameters was unclear. Both water level and paddle rotational speed had negative impacts on the short-circuiting index, while no correlation was observed when varying inlet flow rate. In this study, the optimal operational conditions included low water level (0.1 m) and medium paddle rotational speed (11.6 rpm).

Key words | high rate algal pond (HRAP), mixing characteristics, oxygen transfer rate, residence time distribution

INTRODUCTION

Microalgae have received considerable attention due to their wide range of application. Algal biomass can be used as a source of protein and other high value molecules for human consumption. Their application also expands to the field of agriculture, including fertilizer and animal feed (Lawton et al. 2017), and also energy as material for biofuel production (Voloshin et al. 2016). Especially, when cultured in suitable conditions, microalgae showed a potential oil yield of 58.7 m3/ha/year, while a current terrestrial plant used for producing biofuel only reached 5.4 m3/ha/year (Mata et al. 2010). Moreover, microalgae can use wastewater and flue gas as nutrient sources, thus serving also as a treatment unit (Muñoz & Guieysse 2006). Therefore, in order to apply microalgae cultivation at large scale, many efforts have been spent to study the use of photobioreactor systems to culture microalgae (Muñoz & Guieysse 2006). Among them, the high rate algal pond (HRAP) showed strong advantages including low energy consumption and financial requirement, ease of maintenance and feasibility in expanding to large scale (Kumar et al. 2015).

HRAP is a shallow raceway-type pond with a paddle-wheel as the only source of movement (Park et al. 2010). The system was developed as a result of early intensive studies on photosynthesis in sewage wastewater treatment (Oswald & Gotaas 1957). Since then, HRAP has been applied to treat various types of effluents such as aquaculture (Posadas et al. 2015b), domestic (Posadas et al. 2015a), piggery (de Godos et al. 2009) and industrial (Van Den Hende et al. 2016) wastewaters. Moreover, the system is also recognized for its potential as a sustainable solution for nutrient recovery (Muñoz & Guieysse 2006). Besides wastewater treatment application, it was estimated that HRAP accounted for 95% of large scale microalgae production facilities worldwide (Kumar et al. 2015).

L. A. Pham (corresponding author)
J. Laurent
P. Bois
A. Wanko
ICube, UMR 7357, ENGEES, CNRS,
Université de Strasbourg,
2 rue Boussingault, 67000 Strasbourg,
France
E-mail: le-anh.pham@etu.unistra.fr

doi: 10.2166/wst.2018.461
One major aspect when operating HRAP is the hydrodynamics, because proper mixing allows materials to be evenly distributed in the pond, avoids sedimentation and thus an anaerobic condition. Extensive studies have been conducted to investigate the impacts of pond or paddle-wheel designs as well as some operational conditions on hydrodynamics and energy consumption in the HRAP. Advanced mathematical models were employed to understand flow patterns in the raceway under such influences (Hadiyanto et al. 2013; Hreiz et al. 2014), yet there is still need for experimental validation (Hadiyanto et al. 2013).

Due to its advantages, HRAP can be applied in many places with a wide range of environmental conditions (El Hamouri et al. 1995; Grönlund et al. 2010). Therefore, in order to adapt with each environment, different operational conditions such as inlet flow rate, water level or paddle wheel movement must be adjusted. While the impacts of these conditions on algal growth in HRAP were documented (Sutherland et al. 2015), the combined influences of these conditions on the hydrodynamics of HRAP deserves further investigation. In addition, hydrodynamics is one of the major factors influencing gas transfer in an open aerobic biological reactor like HRAP (Garcia-Ochoa & Gomez 2009). Therefore, varying operational conditions could have a direct impact on gas transfer or biochemical processes and on the performance of the system. How such variations influence gas transfer of an HRAP system should therefore be investigated.

Like other open systems, the HRAP system is sensitive to environmental conditions such as light and temperature variation and to a higher probability of contamination (Mata et al. 2010). Hence, pilot scale studies should be conducted prior to application of the system at full scale in order to have a comprehensive understanding of the system. An appropriate approach may involve (i) studying the impact of operational conditions on HRAP hydrodynamic and gas transfer behaviors at the pilot scale, so optimal operational conditions can be selected, (ii) applying the obtained optimal conditions to the pilot HRAP for wastewater treatment and biomass production, and hence assessing the modification of hydrodynamics and gas transfer due to biochemical processes, (iii) employing the knowledge from pilot studies in designing and operating the system at full scale, using the up-scaling factors determined, (iv) data collected from these studies will finally be used to validate mathematical model supporting system knowledge, management and optimization. This study deals with the first part of the approach, as the HRAP was operated with tap water. Hence the work aims at determining the impacts of operational conditions including water level, inlet flow rate and paddle wheel movement on hydrodynamics in a pilot scale HRAP. To understand how such variation in hydrodynamics impacts gas transfer in an HRAP, the volumetric mass transfer coefficient of oxygen will also be investigated. Finally, an optimal operational condition will be chosen to apply in the pilot HRAP for algal-bacterial biomass cultivation.

MATERIAL AND METHODS

Pilot description

The pilot HRAP consists of a single loop race way pond with two straight channels separated by a separation wall and connected by a 180° bend at each end. The pond had high length to width ratio (L/W) of 19, which is in the optimal range suggested by Hadiyanto et al. (2013). This ratio was similar to L/W ratios found in real scale HRAP systems ranging from 13 for single loop to more than 140 for multiple loop HRAPs (Baya 2012). Hence, geometry similarity between pilot and full-scale systems was respected in this study. A deflector was also placed at each end of the channel to even the flow and decrease the shear stress and dead zone inside the pond (Hadiyanto et al. 2013; Mendoza et al. 2013a). As a consequence, the head loss that depends both on singularity and the change of section throughout the water flow should be reduced thanks to the deflectors. Liquid circulation in the pilot was ensured by a paddlewheel driven by a brushed DC motor (DMN37 K, 24 V, Nidec Servo Corporation, Japan) which was controlled by a bench power supply (ISO-TECH IPS303DD, UK). The paddle blade was designed to cover the entire channel cross section, leaving minimum clearance between the blade and reactor’s wall hence minimizing back flow. Moreover, six blades of the paddlewheel improved paddle efficiency and decreased motor shock (Andersen 2005). The pilot and paddlewheel were made of transparent plastic (Figure 1).

Operational conditions applied

Operational condition applied to the pilot HRAP was the combination of three different operational parameters: water level, paddle rotational speed and inlet flow rate. Due to the capacity of the pilot, three water levels of 0.1, 0.15, and 0.2 m were chosen from the range of operational depths reported by Muñoz & Guieysse (2006) to reach a
total water volume of 72, 108 and 144 L, respectively. Three paddle movements in terms of voltage applied were also selected, representing low (3.5 V for 0.2 ± 0.0 A), medium (7 V for 0.3 ± 0.1 A) and fast (10.5 V for 0.6 ± 0.1 A) mixing. The average paddle rotational speeds obtained were 5.6 ± 0.4, 11.6 ± 0.9 and 16.8 ± 2.1 rpm, respectively, resulting in an expected average water flow as high as 0.3 m/s (Andersen 2005). Due to the water volume, inlet flow rates of 6 and 9 L/h were chosen to obtain 8, 12 and 18 h of HRT depending on the given combination. Overall, 27 experiments were conducted during this study. All the experiments were conducted indoors with a constant ambient temperature of about 20.9 ± 0.6 °C and air pressure of 99.3 kPa. The temperature and air pressure in this study were constant, and thus generated no significant impact on the measurement and calculation. The basic physico-chemical properties of the water used were pH of 7.4 ± 0.1, conductivity of 557.7 ± 1.15 μS/cm and temperature of 15.1 ± 0.4 °C. These values were constant during the experiments, which should provide minimum impact on the results.

**Mixing characteristics and residence time distributions in HRAP**

A classical tracer experiment method was applied to obtain residence time distributions (RTD) due to its availability and effectiveness. Mixing characteristics and RTD of a pilot HRAP under different operational conditions were investigated according to Levenspiel (1999). Following a pulse injection of tracer (NaCl), water conductivity correlated with NaCl concentration was measured by conductivity probe (TetraCon® 325, WTW, Germany) connected to a
multi-parameter portable meter (Multiline P4, WTW, Germany) and recorded with communications software (Multi/Achat II, ver. 1.05, WTW, Germany). Depending on the experiment, the electrode can be positioned at the center of the channel after the paddle wheel (conductivity probe 2) or at the outlet of the pilot (conductivity probe 1) (Figure 1). Suitable amounts of tracer were added depending on the water volume in the HRAP to reduce the uncertainty of electrode measurement: 21.1, 31.6, and 42.2 g of NaCl were injected when the total water volume was 72, 108 and 144 L, respectively.

In order to investigate the mixing characteristics inside the reactor, the pilot was operated in closed condition (without inlet and outlet flows). RTD data obtained from conductivity probe 2 (Figure 1) were calculated following Mendoza et al. (2013a) to compute the Bodenstein number (Bo) and circulation time. These values were then used to assess mixing characteristics inside the HRAP. Moreover, in practice, an HRAP is usually operated in continuous condition, thus RTD data from experiments with continuous operational conditions (conductivity probe 1) (Figure 1) were calculated based on Levenspiel (1999) and used to evaluate the hydrodynamic behavior of the pilot HRAP. Due to the stability of the pilot in long term operation, only 0.1 and 0.15 m of water level were applied in continuous mode. Similarly, the highest paddle rotational speed achieved at 10.5 V was only applied with 0.1 m of water level and 6 L/h of inlet flow rate. The detailed calculation procedure is indicated in the Appendix (available with the online version of this paper).

**Volumetric mass transfer coefficient (k_L, a) in HRAP**

Volumetric mass transfer coefficient (k_L, a) in a bioreactor is used to assess gas transferring efficiency as well as the effects of the operational conditions on gas mixing (Garcia-Ochoa & Gomez 2009). The dynamic method is widely applied to study the impacts of operational conditions on the k_L, a (Garcia-Ochoa & Gomez 2009) and hence was chosen to determine the k_L, a of the pilot HRAP.

The determination of the volumetric mass transfer coefficient of oxygen (k_L, aO2) under different operational conditions was performed following the European standard (NF EN 12255-15). Evolution of dissolved oxygen (DO) in water was measured by a DO electrode (WTW Inolab Oxi Level II DO Meter) connected to a multi-parameter portable meter (Multiline P4, WTW, Germany) and recorded with communications software (Multi/Achat II, ver. 1.05, WTW, Germany). Data recorded by two DO electrodes positioned at the center of different channels (Figure 1) were used to calculate k_L, aO2 following the procedure reported by Garcia-Ochoa & Gomez (2009), taking into account the dynamic response of the electrodes.

**Sensitivity analysis**

Two sensitivity functions were used: the absolute-relative (a-r) sensitivity function, measuring the absolute change in the variable for a 100% change in input parameter, and the relative-relative (r-r) sensitivity function, measuring the relative change in the variable for a 100% change in input parameter. The a-r sensitivity was used for quantitative comparisons of the effect of different parameters (water level, paddle rotational speed) on a common variable y (Bo, k_L, a). The r-r sensitivity was used to compare effects of different parameters on different variables (Reichert 1994). One-way analysis of variance (ANOVA) followed by Holm tests (95% confidence interval) was applied in R software (version 3.3.1 (2016-06-21)) to compare these effects. The detailed calculation procedure is indicated in the Appendix.

**RESULTS AND DISCUSSION**

**Water flow regime**

In order to assess the similarity between water flow regimes in different systems, Reynolds (Re) and Froude (Fr) numbers are commonly used. Table 1 presents the Reynolds and Froude numbers for the operational conditions applied in this study. High levels of Re obtained in all of the modalities tested suggests the dominance of turbulent flow in the HRAP, which is in agreement with the real-scale HRAP of between 1.6*10^4 and 18*10^4 (Baya 2012). It was also

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Reynolds and Froude numbers for different operational conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modality</td>
<td>3.5V10</td>
</tr>
<tr>
<td>Re (*10^4)</td>
<td>1.55</td>
</tr>
<tr>
<td>Fr</td>
<td>0.16</td>
</tr>
</tbody>
</table>

With xVy modality corresponds to x Voltage and y cm water depth. Re stands for Reynolds while Fr stands for Froude.
indicated that turbulence occurring in HRAP enhances light/dark frequencies and the mass transfer rate, hence improving productivity and photosynthetic efficiency (Grob-belaar 1994). Moreover, values of Fr calculated in all tests indicate that subcritical or fluvial flow occurred in the HRAP. These results are generally higher than the values commonly found among full scale HRAP systems (0.02 to 0.13) (Baya 2012) which was mainly due to the high velocities obtained in the experiments. However, in all cases, subcritical flow was dominant in the system. Hence, the pilot HRAP applied in this study shares similar characteristics with other real scale HRAP in literature.

Paddle wheel vs water level on HRAP performance in closed condition

The Bodenstein (Bo) number was calculated according to RTD data obtained from the pilot with different operational conditions. This parameter quantifies the ratio between total momentum and molecular mass transfers to solute transport within the system (Levenspiel 1999). High values of Bo in every experiment suggested plug flow behavior in the pilot HRAP, which is in accordance with the literature (El Ouartghi et al. 2000). Results indicated that Bo had positive correlation with paddle rotational speed but negative relation with water level (Figure 2(a)). The average water velocity along the raceway channel, directly correlated with Bo, was also calculated (Figure 2(b)). In practice, it was suggested that a water velocity of 0.2 to 0.3 m/s was sufficient for an HRAP. In this study, the required velocity was satisfied even with the lowest rotational speed (5.6 rpm). The highest speed (16.8 rpm), although improving mixing in the pond, may cause higher shear stress on algal cells and more energy consumption (Andersen 2005). Obviously, paddle rotational speed had a strong influence on the circulation in the raceway and their correlation was positive. This relationship was also shown when assessing average mixing time: 318, 165, and 127 s with the rotational speed at 5.6, 11.6, and 16.8 rpm, respectively. The change in water level had a small impact on water velocity (Figure 2(b)). Therefore, similar levels of momentum at different water levels were expected when applying similar rotational speed. However, the impact was more significant on Bo. This may come from the fact that a higher water level results in a higher total water volume in the HRAP and thus increases the molecular mass transfers within the reactor and reduces the Bo value (Figure 2(a)).

Absolute-relative sensitivity analysis was applied to assess the impacts of operational parameters on mixing (Bo). It showed that at one water level, Bo was more sensitive to the change of paddle rotational speed from 11.6 to 16.8 rpm than from 5.6 to 11.6 rpm. Moreover, as the water level increased, the sensitivity of Bo with paddle rotational speed also increased (Figure A1(a), Appendix, available with the online version of this paper). On the other hand, except at the highest paddle rotational speed, Bo was more sensitive to the change of water level from 0.15 to 0.2 m than from 0.1 to 0.15 m. As the paddle rotational speed decreased, the sensitivity of Bo to water level increased (Figure A1(b), Appendix). Since the Boden-stein number represents the ratio of the total momentum transfer over the molecular mass transfer, any increase in Bo value may lead to an increase in advection and hence shear stress, which can damage algal cells (Mata et al. 2010). Therefore, the amplification of Bo sensitivity with paddle rotational speed at high speed and/or high water level should be considered before choosing the operational conditions for HRAP.

Figure 2 | Influence of paddle rotational speed, water level to Bodenstein number (a) and water velocity (b) in pilot HRAP.
Dominant effect of paddle wheel on oxygen transfer in HRAP

Values of volumetric mass transfer coefficient of oxygen ($k_{LaO_2}$) according to each operational condition were calculated from experimental data. The impact of different operational conditions on the gas transfer rate was discussed by comparing these values. The data recorded at two positions were similar because of the small scale of the pilot and hence only data from the second position (DO probe 2) were used for $k_{LaO_2}$ calculation. It showed that $k_{LaO_2}$ in HRAP had a positive correlation with paddle rotational speed and negative correlation with water level, which was in good agreement with the Bo values obtained (Figure 3). In general, values of $k_{LaO_2}$ obtained from this study are comparable with HRAP having an air diffusion system (Mendoza et al. 2013b) and higher than classical HRAP systems (El Ouarghi et al. 2000). It suggests that higher paddle rotational speed causes more mixing in water and thus more oxygen can be transferred. In addition, for the same mixing and surface area applied, a higher water level (higher volume of fluid) in the reactor increases the time required to have a balanced DO level and thus decreases $k_{LaO_2}$.

Results from sensitivity analysis indicated that $k_{LaO_2}$ was more sensitive to the change of paddle rotational speed from 11.6 to 16.8 rpm than from 5.6 to 11.6 rpm. The reduction of water level also caused higher sensitivity of $k_{LaO_2}$ to paddle rotational speed (Figure A2(a), Appendix, available online). Water level changes from 0.1 to 0.15 m caused more change in $k_{LaO_2}$ than changes from 0.15 to 0.2 m. As the paddle rotational speed decreased, the sensitivity of $k_{LaO_2}$ to water level also decreased, with the only exception in rotational speed of 5.6 rpm (Figure A2(b), Appendix). In practice, a better gas transfer rate benefits the HRAP system by reducing the occurrence of oxygen saturation or anaerobic conditions, and hence avoid stressful conditions for algae. Therefore, the increased sensitivity of $k_{LaO_2}$ at high paddle rotational speed and/or at low water level should be considered.

Operational condition impacts on HRAP performance in closed condition

To compare the impacts of different operational parameters including water level, and paddle rotational speed on $k_{LaO_2}$ and Bo in closed operational conditions, relative-relative sensitivity of $k_{LaO_2}$ and Bo with water level and paddle rotational speed was employed (Figure 4). The $k_{LaO_2}$ was more sensitive to paddle rotation than water level ($p$ value <0.05). In addition, the sensitivities of Bo to water level and paddle rotational speed were similar ($p$ value >0.05). On the other side, water level had similar sensitivities with $k_{LaO_2}$ and Bo ($p$ value >0.05), while paddle rotational speed had higher sensitivity with $k_{LaO_2}$ than with Bo ($p$ value <0.05). These results suggested stronger impacts on $k_{LaO_2}$ from paddle rotational speed than from water level. A similar degree of influence was seen between water level and paddle rotational speed on Bo. Moreover, paddle rotational speed had more impacts on $k_{LaO_2}$ than on Bo. This may suggest changing paddle rotational speed would be more efficient if one wants to improve the $k_{LaO_2}$.

Impacts of operational conditions on residence time distributions in HRAP

The global transport parameters for each set of operational conditions were derived from RTD functions to quantitatively assess the hydrodynamics in the pilot HRAP under
these conditions. Values of the most representative parameters including effective volume fraction (ε), short-circuiting index (SI), and Peclet number (Pe) in different operational conditions were compared (Figure 5). Detailed calculations and other transport parameters calculated are shown in the Appendix.

Different water levels change the total water volume in the reactor, thus effective volume fraction (ε) is used to compare the impact of operational conditions on effective volume. A higher inlet flow rate resulted in a higher effective volume fraction inside the HRAP except for the case of 11.6 rpm paddle rotational speed with 0.1 m of water level (Figure 5(a)). At the same water level or the same working volume, a higher inlet flow rate leads to a higher volume fraction coming in and out of the reactor at the same time, which could result in a positive impact on internal mixing or lowering the stagnant volume of the reactor. Paddle rotational speed had a negative impact on ε, with higher rotational speed resulting in lower ε. Moreover, the impact of water level on ε was not clear in this study. These results were in contrast with conclusions made using a simulation model, where increasing the water velocity decreased the dead zones while a higher water level led to a higher volume of dead zone (Hadiyanto et al. 2015). This may partly be due to the differences between conditions, shapes and sizes applied in each study, which deserves more comprehensive investigation. Another difference between this study and simulation was the fraction of dead zone: experimental results from this study were about two times higher than simulation results. However, these differences could be explained by the global calculation of ε from RTD data in this study and the definition of the dead zone in the simulation (Hadiyanto et al. 2015).

Figure 5  | Influence of inlet flow rate (a, d, f), paddle wheel rotation (b, e, g) and water level (c, f, h) to effective volume fraction (ε: a–c), short-circuiting index (SI (%): d–f) and Peclet number (Pe: g–i) in pilot HRAP.
In general, low short-circuiting indexes (SI) suggested negligible proportions to the total volume of the pilot HRAP. Although inlet flow rate showed no impact on SI (Figure 5(d)), paddle rotational speed and water level showed negative influences on this parameter (Figure 5(e) and 5(f)). As mentioned above in the mixing characteristics study, higher rotational speed resulted in lower time required for total mixing, thus decreasing bypassing in the reactor. One exception noticed was at the highest rotational speed, which had a higher SI value (Figure 5(e)). This could be explained by taking account of the short channel of the pilot HRAP, because although having the lowest mixing time, this time was still not low enough to compensate the bypassing effect due to the fast flow rate in the channel. The negative impact of water level on SI could be explained by considering the volume fraction of inlet and outlet flow with each water level. As the water depth increases, the volume fraction of inlet and thus outlet flow at one time decreases, resulting in a lower SI value.

Although the result from the mixing characteristics study showed that the internal flow in the pilot was dominated by plug flow, the result in the systemic study showed a high level of dispersion in comparison with advection (Figure 5(g)–5(i)). These results, however, did not contradict each other since the channeling design of HRAP is to favor plug flow which the coming materials are mixed in short time. Hence, the whole pilot HRAP can be considered as a continuous stirred-tank reactor (CSTR). The negative impact of inlet flow rate on Pe may come from the improvement of internal mixing, which increases dispersion in the pilot when a larger volume flows in and out of the reactor (Figure 5(g)). This was correlated with the results of ε observed above (Figure 5(n)). The impact of paddle rotational speed on Pe displayed an opposite trend (Figure 5(h)): higher speed gave a higher Pe value. As observed above, higher rotational speed led to higher water velocity (Figure 5(b)) and thus increased the advective contribution, increasing Pe. Finally, the impact of water level on Pe was not clear (Figure 5(i)).

**Optimal operational conditions for algal-bacterial growth in HRAP**

Since the inlet flow rate is usually regulated according to practical circumstances, the impact of inlet flow rate variation on internal mixing should only be considered where necessary. Besides the practical reason indicated above, although resulting in the highest level of mixing and thus the highest gas transfer rate, the highest paddle rotational speed (16.8 rpm) should also not be chosen for consideration due to the low ε and potentially high shear stress obtained, which generate negative impacts on microorganisms (Sutherland et al. 2015). This study also indicated that, as the water level increased, the negative impact of the water level on mixing and thus gas transfer also increased. Therefore, the highest water level (0.2 m) should not be chosen due to its low mixing level and \( k_{LaO_2} \). Moreover, the highest rotational speed and water level also required high energy consumption, which should be avoided in this study.

As indicated above, mixing is vital to the performance of HRAP. Besides preventing biomass sedimentation, good mixing also ensures that algal cells receive enough light for photosynthesis. Moreover, a high level of mixing also results in a high gas transfer rate, which is important especially to decrease the occurrence of oxygen oversaturation or ammonia accumulation in the HRAP (Park et al. 2010). Due to the argument above, the low (5.6 rpm) and medium (11.6 rpm) rotational speeds are considered. Although 5.6 rpm provided higher ε and lower SI, which may better support HRAP performance, these differences were small and can be compensated for by the benefit of higher gas transfer. Therefore, the medium (11.6 rpm) speed should be applied for algal-bacterial growth.

Water level determines the light penetration into the culture and thus should be as shallow as possible to maximize the amount of light provided to algae (Andersen 2005). After eliminating the highest value, two water levels of 0.1 and 0.15 m are considered, with the former resulting in a higher level of mixing and thus a higher gas transfer rate. Although low water level also leads to thermal instability, causing growth inhibition (Sutherland et al. 2015), this risk is higher when applying the HRAP in an outdoor condition. Therefore, with the indoor condition in this study, the low water level of 0.1 m was the better option.

It was shown that variation of operational conditions resulted in changes in hydrodynamics and gas transfer in the HRAP. In order to apply the pilot for algal-bacterial growth, the chosen operational conditions should have positive impacts on the biochemical processes inside. Therefore, the best combination of operational conditions in this study should be between a water level of 0.1 m and paddle rotational speed of 11.6 rpm.

**CONCLUSION**

In this study, different combinations of water level, paddle rotational speed and flow rate were applied to investigate
their impacts on mixing characteristics, RTD and gas transfer coefficients of the pilot HRAP. In general, the pilot HRAP shared similar characteristics with other real-scale HRAPs and was dominated by turbulent flow in its channel. Moreover, the HRAP showed a good mixing level even with the lowest paddle rotational speed applied, and hence the entire HRAP can be considered as a CSTR. In closed condition, the Bodenstein number, water velocity and oxygen transfer coefficient had a positive correlation with paddle rotational speed but a negative correlation with water level, although the impact of water level on linear velocity was small. The amplification effect of water level and paddle rotational speed on the sensitivity of Bo and $k_L a O_2$ should be noticed and considered before applying operational parameters to an HRAP system. Paddle rotational speed had more impact on $k_L a O_2$ than on Bo. In an open condition, effective volume fraction ($\epsilon$) had a positive correlation with inlet flow rate and a negative correlation with paddle rotation, while the opposite was observed in the case of Pe. Variation of water level shows an unclear impact on these parameters. Both water level and paddle rotational speed had negative impacts on SI, while no correlation was observed when varying inlet flow rate. The best combination of operational conditions for algal-bacterial growth in HRAP is between low water level ($0.1\, m$) and medium paddle rotational speed ($11.6 \, rpm$). These data obtained could be useful for (i) algal-bacterial growth for waste water treatment and biomass production and (ii) calibrating a 3D hydrodynamic model for better studying the impact of operational conditions on HRAP. Moreover, a further step would be to apply the knowledge achieved from pilot studies for designing and operating outdoor large scale HRAP system, so the up-scaling factors can be evaluated.

**REFERENCES**


Park, J. B. K., Craggs, R. J. & Shilton, A. N. 2010 *Wastewater treatment high rate algal ponds for biofuel production*. *Bioresource Technology* 102 (1), 35–42.


wastewaters. Journal of Chemical Technology & Biotechnology 90 (6), 1094–1101.

First received 5 March 2018; accepted in revised form 23 October 2018. Available online 31 October 2018