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Verification of Dead Zones Generated in Bioreactors as a Proactive Stage in Bioreactor Design

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ABSTRACT

The activity and growth of microorganisms for renewable energy production are still influenced by the dead zones created in bioreactors. These areas form a nutrient and thermal gradient, causing an abundance of food in certain areas compared to famines in other areas of same bioreactor. The current study is a step in identifying those dead zones, followed by another step in improving the flow of media inside the reactor. The results indicated that the inner parts of the bioreactor may be a crucial factor in the creation and spread of such dead zones. For example, the position of the disc-type diffuser contributes to the generation of those areas at the bottom of the reactor. It was inferred from the fluid movement in reactors using the annular-type diffuser proposed in the current study. The bubble size, gas mass flux, and radiuses of fillet, as the most important factors, were examined in both bioreactors. The results revealed a noticeable improvement in these parameters in this area of the reactor when the disc diffuser was replaced by the annular diffuser. For example, the average liquid velocity was recorded in the lower part of the modernized reactor at 0.0198 m/s, while the velocity was recorded in the conventional reactor at 0.00077 m/s under same bubbles diameter used in both reactors (0.125 mm). The inclusion of the effect of the presence of microorganisms in mathematical models was also addressed in the current study. The results showed that the amount of oxygen remaining at the bottom of the reactor after bio-consumption in the presence of the annular diffuser was higher than that in the conventional reactor. This clearly emphasizes the importance of the design of the internal parts of the bioreactor.

Keywords: bioreactor, dead zones, flow pattern, mass transfer, modeling.

INTRODUCTION

In recent years, bioreactors renewable energy production has experienced impressive technological advancement [Negi, et al., 2023; Liu, et al., 2022]. Several parameters affect how the design will achieve its desired aims. For instance, the nature of the living microorganism, optimal operational conditions for growth and reproduction, as well as the nature of the function assigned to it [Li et al, 2022; Mu, et al., 2021; Abdulmajeed and Ibrahim, 2018; Al-Mashhadani, and Khudhair, 2017]. The bubbling-type bioreactors feature reduced control necessities and lower shear drives as compared to other mechanical internal components in conventional fermenters [Zhang, et al. 2019; Yank, et al., 2018; FU, et al., 2003]. However, the challenges of mixing, maintenance, and stability in bioprocesses persist even with the advancements in bioreactor technology [Moradi et al., 2021]. In anaerobic digestion, as example, the traditional digester employing stirred tanks may provide superior energy products, but these systems become economically unviable when process energy needs are compared to the energy gained [Al-Mashhadani et al., 2015(a)].

One of the bubbling-type bioreactors is air/gas-lift-type. It is receiving wide attention for their many advantages over conventional reactors. With existing of the inner draft tube in the airlift bioreactor, the gas bubbling system causes a medium to up-flow with suspended nutrients and living microorganisms [Hanspal et al., 2020; Salazar-Magallon and Huerta, 2020; Al-Mashhadani, 2017].

The medium is then directed to down-flow via the gas-free downcomer area, while the gas escapes from the bioreactor's top [Marroquin-Fandino et al., 2020]. In such loop bioreactor systems, the circulation of the liquid phase allows the solid/dissolved nutrients to be retained in suspension even when working with low liquid-gas velocities. Numerous studies have focused on the inner structure components of photo-bioreactors to enhance transfer phenomena, offer suitable operating conditions, and make it easier for microorganisms to access nutrients [Sastaravet, et al., 2020; Miodrag, et al., 2014; Yang,et al. 2018; Zhang et al., 2017]. Operational problems were also addressed in order to enhance the bioreactor's performance [Paladino and Neviani, 2021]. For instance, by controlling the gas bubbles' diameter to increase the surface area-volume rate, a significant improvement in the mass transfer between the gas and liquid was achieved [Abadie et al., 2022; Tesar V., 2020; Zimmerman, et al. 2013]. As a result, it accelerates the removal of waste gases produced by the metabolism processes of microorganisms in the bioreactor, such as essential gases [Neviani, et al. 2021]. This method has the added benefit of extending the gas phase time of retention in culture media, which lengthens the time it takes for gas and liquid to transfer between them [Yang et al. 2013]. However, using diameters smaller might result in a gradient in the reactor's nutrient concentration and harvesting procedures throughout the cultivation phase. It would significantly lower the biological process's performance coefficient. But this was taken advantage of in the chemical and biological separation procedures [Hanotu, et al., 2013].

One of the crucial internal components of the bioreactor is the gas diffuser, which influences how well the gas-liquid dispersion occurs there [Qiao, et al., 2023]. The diffuser's position at the bottom of the bioreactor helps to reduce dead zones and improve mixing efficiency, which results in a uniform distribution of nutrients and the right operating conditions [Al-Mashhadani et al. 2015(b)].

However, biological processes frequently include solids or suspended materials, which lead to their buildup in the reactor's bottom portion and the clogging of the diffuser nozzles. A measure to solve this issue was proposed by Al-Mashhadani et al. 2015(b) who advised a certain height for the diffuser. They concluded the appropriate height of the diffuser is 5% of the total height of the reactor. This step achieved some improvements in bioreactors, as well as it was associated with the efficiency of micro-bubble technology in biological processes. However, through several experiments, the current study showed the presence of dead zones generated at the bottom of the reactor, while the velocity available in that area is not sufficient to move the culture medium in several bioprocesses such as dairy wastewater. The current study dealt also with this topic by analyzing the dead zones in a bioreactor with a proposal to use the annular diffuser instead of the disc diffuser as a new design for bioreactors.

MATERIAL AND METHODS

A gas-lift bioreactor was used in the current investigation with dimensions of 300 mm height, 150 mm diameter and the height of the draft tube was 200 mm. In traditional design, the diffuser type was a disc whose diameter and height was 80 mm, and 10 mm respectively. While in the proposed design in the current study, the bioreactor was equipped with an annular diffuser. In order to achieve a logical comparison between the traditional diffuser type and the proposed diffuser type, the dimensions of the annular diffuser were chosen to achieve equality in the surface area of the two diffusers. Therefore, the inner diameter of 42 mm and the outer diameter of 62 mm were adopted in the current study, as shown in Figure 1.

The air was used as a source of oxygen for the bacteria, while the nitrogen helped remove the carbon dioxide produced from the metabolic processes. Five radiuses of fillet in the bottom part of the bioreactor (0, 10, 20, 30, and 40 mm) were applied in the current study. The current modeling took into account the size of the bubbles prepared for the bioreactor as a key factor affecting the movement of liquid and gas, as well as the effective role on mass transfer between the gas and the culture medium. The diameters of the bubbles in the both bioreactor used in the current study were 30–1000 μm.

The time-dependent conservation of momentum and energy equation and the time-dependent continuity equation for mass conservation make up the equations that are used in the current study. The adapted laminar flow dynamic model was included the transfer of gas from air bubbles to the liquid phase through the following equations:

$$\nabla.\left[\emptyset_l \eta_l \left(\nabla u_l + (\nabla u_l)^{\mathrm{T}}\right)\right] + \emptyset_l \rho_l g = \\ = \emptyset_l \rho_l \frac{\partial u_l}{\partial t} + \emptyset_l \rho_l (u_l.\nabla) u_l - F \quad (1)$$

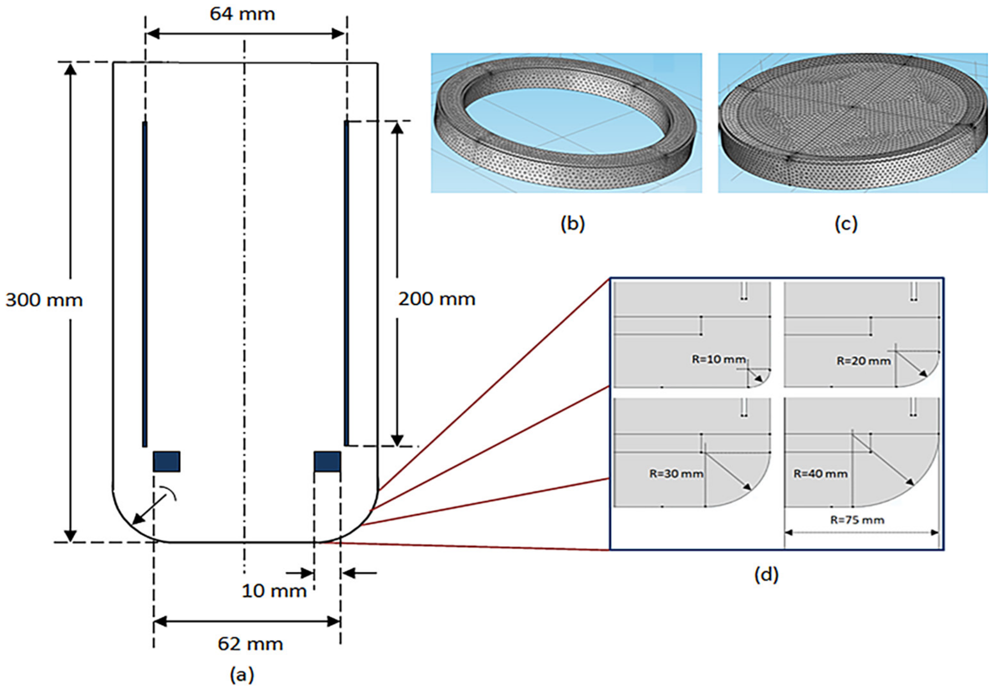

Figure 1. Modified bioreactor used in the current study: (a) structure and dimensions of bioreactor, (b) annular diffuser, (c) disc diffuser, (d) fillet corner with different radiuses

$$\frac{\partial \emptyset_g \rho_g}{\partial t} + \nabla.\mathrm{N}_{\rho_g \emptyset_g} + M_{gl} = 0 \tag{2}$$

where: $\emptyset_l$ and $\emptyset_g$ – defined as volume fraction (m^3/m^3) in liquid phase and gas phase respectively;
η_l – dynamic viscosity of liquid kg/m^3;
u_l – a liquid velocity (m/s);
ρ_l – a density of liquid phase kg/m^3;
g – gravity;
F – volume force N/m^3, t – time (s).

To describe the multiple flow patterns, a laminar bubbly flow model in COMSOL Multiphysic was employed. In the current work, an axially symmetric two-dimensional model has been used to simulate an airlift bioreactor. Relative velocity was calculated using the pressure-drag balance that was derived from the slip model. Given this velocity of two-phase fluids, it is possible to calculate the gas velocity. No slip or gas flow values were employed in the boundary conditions for the liquid phase and gas phase on the draft tube and internal walls, resulting in values of velocity of gas and liquid equal to zero. On the surface of both diffusers, the following equations were used in different mass gas flux.

$$-n.N_{\rho_g \emptyset_g} = N_{\rho_g \emptyset_g} \tag{3}$$

$$-n.N_{\rho_g \emptyset_g} = N_n \tag{4}$$

where: n is number density ($1/m^3$).
On the other hand, for the gas phase and liquid phase, respectively, the "gas exit" and the slip boundary conditions were utilized at the top of the liquid phase with these equations:

$$K - (K.n) = 0 \tag{5}$$

$$K = [\mu_l(\nabla u_l + (\nabla u_l))]n \tag{6}$$

The time-dependent of the bio-consumed of dissolved oxygen in the bottom part of the bioreactor by present microorganisms was according to the following equation:

$$-\frac{dC_i}{dt} = K^f \prod_{i=1}^{Q} C_i{}^v \tag{7}$$

where: K^f – a constant rate of consumption;
C_i^v – concentration of the biologically consumed oxygen, ($mol/m^3.s$).

RESULT AND DISCUSSION

The current study was preceded by several attempts to identify and assess some of the problems that came up during the manufacture of anaerobic digestion-derived biogas and the bioreactors used to produce microalgae-derived biofuels. Anaerobic digestion suffered more in the generation of dead zones compared to reactors that were used for microalgae culture. The main reason for this discrepancy is the nature of the culture medium used in this unit. It was distinguished by its high viscosity and thickness because it contained complex organic substances (proteins, carbohydrates, fats.....etc). The culture medium used in the cultivation of microalgae, in the other hand, is very close to the nature of water in the early stages of growth, but these properties soon change with time depending on the operation conditions and type of algae strain used. Thus, some dead zones have been diagnosed through sedimentation in certain areas of the bioreactor. The current work used Comsol Multiphysics to construct certain internal bioreactor elements that specifically target the dead zones generated and to precisely diagnose these areas. In addition to a parametric analysis of bubble size, effect gas mass flux, and mass transfer, the investigation was conducted with and without living microorganisms in the bioreactor.

Effect of bubble size

The interfacial area between the liquid-gas phases is a driving force for improving mass and heat transfer. It depends on several variables, including the ratio of the surface area of the bubbles to their volume. Therefore, the effect of the bubble size on the dead zone regions at the bottom section of the reactor was considered in the current study. The study was also carried out using two types of diffusers (annular and disc). Figure 2 shows that increasing the surface area of the bubbles relative to their volume by reducing the size of the used gas bubbles achieved a significant improvement in the movement of the liquid in this part of the reactor. Reducing the size of the bubbles from 1×10^{-3} m to 1.6×10^{-4} m, for example, has increased the average liquid's velocity in the both bioreactor. This increase in liquid velocity as a result of reducing the bubble size of air has also been proven in previous studies, but the focus was on other parts of the reactor (i.e. in the riser and downcomer region) as can be seen in the Al-Mashhadani et al, 2015(b). The identified reason was due to the thrust exerted by the large swarm of bubbles. However, the buoyancy force of the bubbles and their distribution over large areas of this part of the reactor hindered the continued increase in the average velocity of the liquid. That is, it represents a barrier that prevents the liquid from entering the lower region of the reactor. Therefore, the decrease in fluid velocity is observed in both reactors with the reduction of the diameter of the bubbles used in the current study.

Although the effect of a decrease in the fluid velocity in the reactor equipped with the disc diffuser was greater, the design of the annular diffuser and its effect on the movement of the liquid in this lower part of the bioreactor remained at the forefront in terms of the value of the velocity of the liquid. For example, the average liquid velocity was recorded in the lower part of the suggested bioreactor at (0.0198 m/s), while its velocity was recorded in the conventional reactor at (0.00077 m/s) of the same diameter as the bubbles used in both reactors (0.125 mm). The

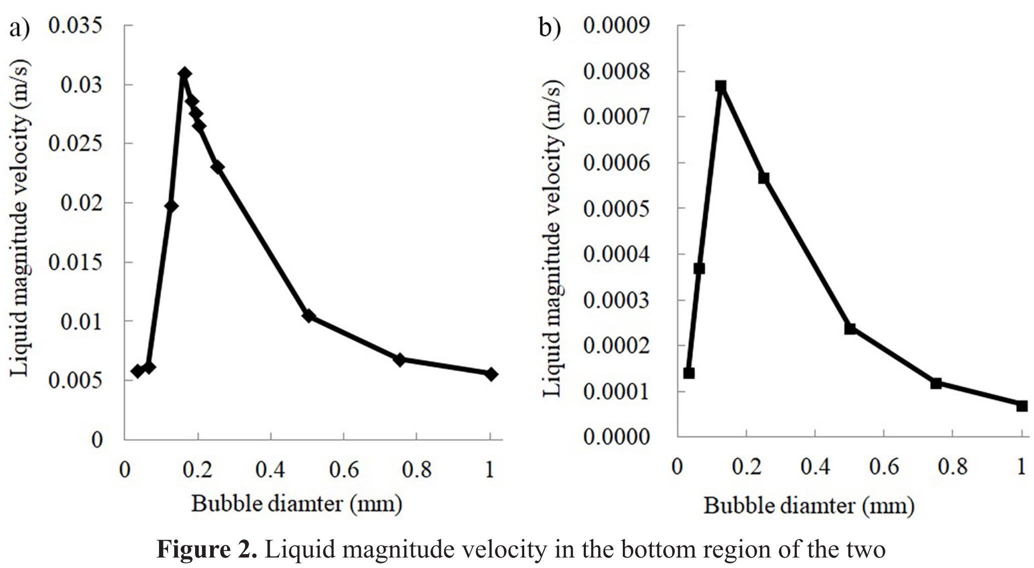

Figure 2. Liquid magnitude velocity in the bottom region of the two reactors equipped by (a) annular diffuser and (b) disc diffuser

modified bioreactor recorded the greatest average liquid velocity at a bubble diameter of 0.160 mm relatively, whereas the conventional reactor recorded the highest average liquid velocity at a bubble diameter of 0.125 mm relatively.

Effect of gas mass flux

The gas mass flux is one of the options available to increase the mass transfer between the culture medium and the gas bubbles, thus, delaying the concentration equilibrium between the two phases as well as improving the mixing efficiency and preventing temperature gradient in the bioreactor. The current study chose this variable as an attempt to improve the mixing efficiency in the lower part of the bioreactor. The study was to choose different gas mass fluxes (0.00698 to 0.02198 kg/(m^2.s)) to study the effect on the rate of liquid pattern regime in that downstream, as shown in Figure 3. The only supply of fluid to the bioreactor's bottom part is through the downcomer area; therefore an increase in the liquid's circulation rate enhances the movement in this part of the reactor. The figure demonstrates that an increase in the gas flow rate in the riser area has significantly increased the liquid flow rate in the reactor's lower portion for both reactors. However, it is possible to see how the annular diffuser positively affects this improvement.

With respect to the gas bubbles, they are only rising in the riser region at low gas flow rates while fluid circulation is relatively slow. A few gas bubbles can be drawn into the downcomer by the liquid as the gas velocity rose along with the liquid circulation rate [Chisti and Moo-young, 1987]. The utilization of microbubbles, however, could make it possible to access even the dead zones reported in the present investigation. This gives an advantage to gas-microbubbles technology in this aspect. But, the current study used the large bubble sizes relatively; being the most used in biological processes, and therefore the possibility of these bubbles reaching the lower part of the reactor is rare.

Effect of fillet corners

The current study also took the corners shape into account in the investigation of dead zones in bioreactors. Accumulated particles as a result of the very little liquid movement were observed at the right angles (90°) of the bioreactor. Fillet the corners were one of the variables that were addressed in the present modeling for the bioreactor equipped with a disc diffuser and that equipped with an annular diffuser. Five radiuses of fillet in the bottom part of the bioreactor were applied in the current study, as shown in Figure 1 and Figure 4, which shows liquid magnitude velocity in the bottom region of the two bioreactors equipped by annular diffuser and disc diffuser using different radiuses of fillet (0.01, 0.02, 0.03, 0.04 m).The outcomes demonstrated some improvement when utilizing reactors with disc diffusers; however, there was no clear improvement with reactors using annular diffusers as can be seen in Figure 4. However, due to the ease of maintenance and to prevent particulate matter accumulation, the current study preferred to use fillet-angle for biological applications.

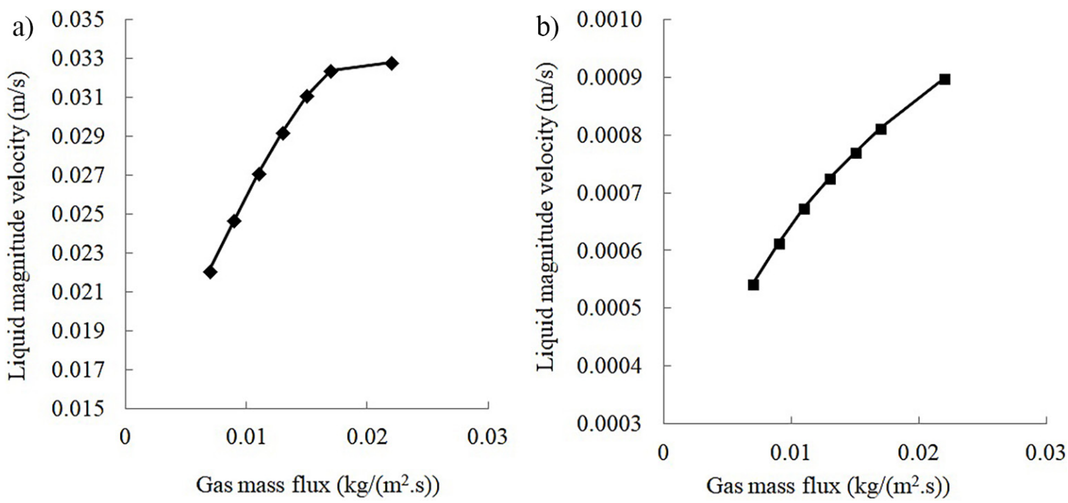

Figure 3. Liquid magnitude velocity in the bottom region of the two reactors equipped by (a) annular diffuser and (b) disc diffuser using different gas mass flux

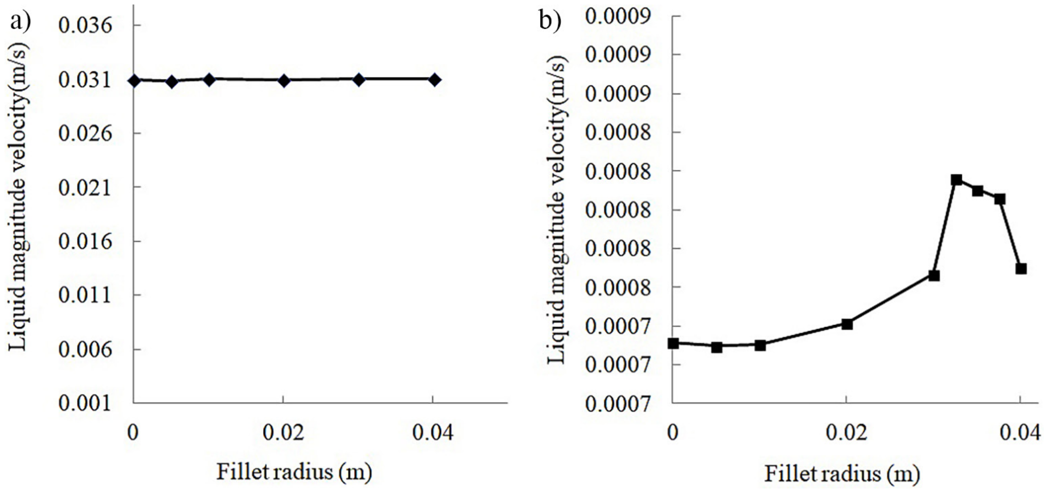

Figure 4. Liquid magnitude velocity in the bottom region of the two reactors equipped by (a) annular diffuser and (b) disc diffuser using radiuses of fillet (0.01, 0.02, 0.03, 0.04 m)

Mass transfer in free of microorganisms system.

Figure 5 shows the concentration of dissolved oxygen in the bottom part of the bioreactor when the reactor is equipped with the annular and disc diffusers in absence the microorganism culture.

In the current study, a bioreactor for the growth of aerobic bacteria was proposed as the fermentation process. As a result, the reactor contains oxygen gas, a component required for aerobic microorganisms, and it also removes carbon dioxide produced by bacterial metabolism from the culture media. In real applications, however, call for using air as a required step to cut costs rather than pure oxygen gas. In addition, the nitrogen gas was used to purge the bioreactor of the produced metabolite gases while also relying on air as a gas supply for oxygen. For the investigation of mass transfer from the gas to the reactor, the optimal operating parameters that had previously been investigated were accepted as a reliable foundation. The process of testing and comparing both reactors equipped with a disc diffuser with that of a bioreactor equipped with an annular diffuser. The kinetic, transport properties, and thermodynamic properties was transferred to time depended models via the synchronize with Comsol Multiphysics in this study. The obtained data show the acceleration in the concentration of dissolved oxygen in both reactors. However, the results also confirmed conclusively that the dissolved oxygen concentration in the reactor equipped with the annular diffuser was more dissolved in the other reactor as can be also seen in Figure 6. This

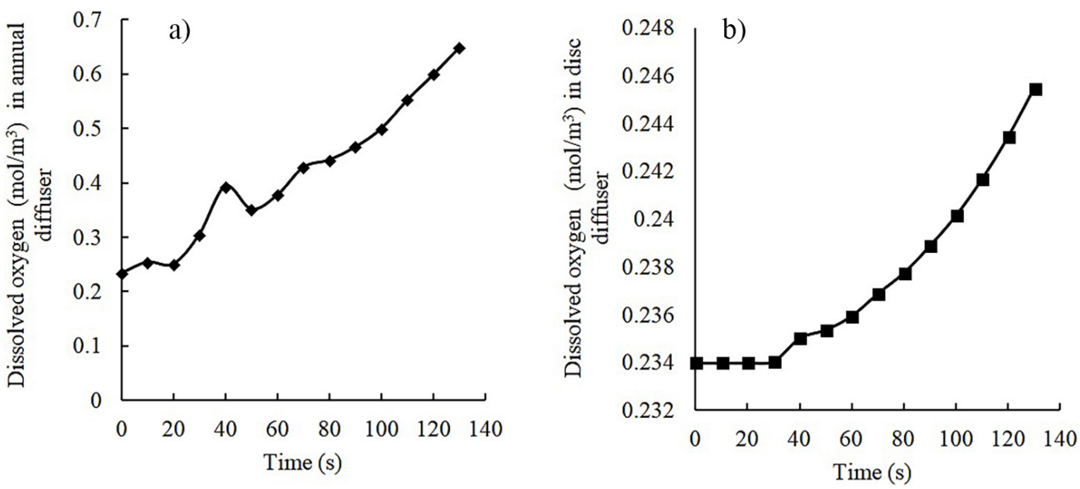

Figure 5. Concentration of dissolved oxygen in the bottom region of the two reactors equipped by (a) annular diffuser and (b) disc diffuser

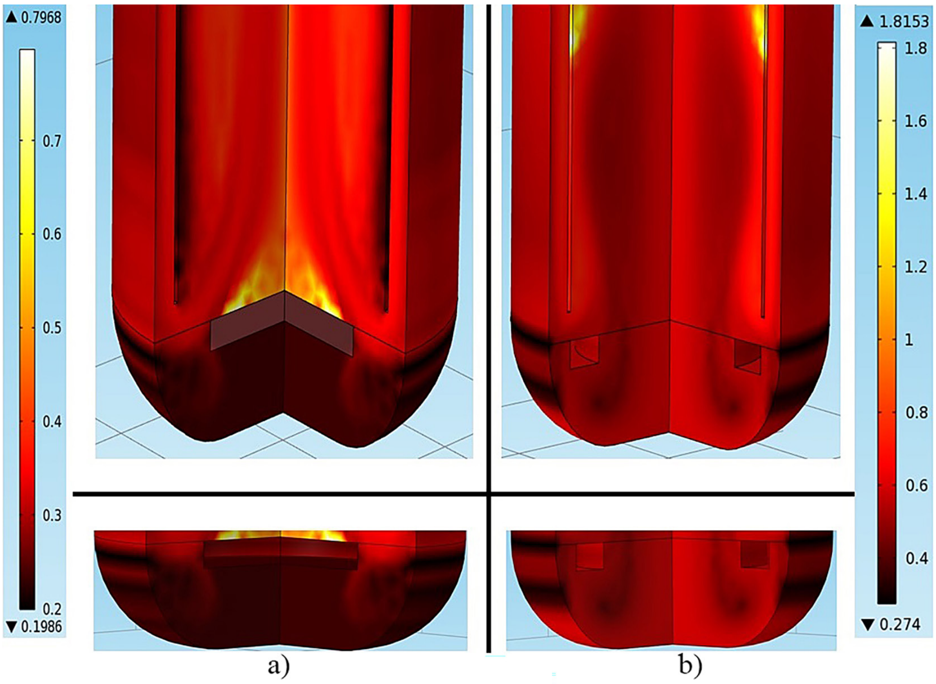

Figure 6. Oxygen concentration profile in the bottom part of bioreactor in free of bio-consumption process (a) disk diffuser, (b) annular diffuser

supports what was previously stated in the current study on how the culture medium mobility affects the rate of mass transfer between gas and liquid. This diagram (i.e Figure 6) also demonstrates the patterns of oxygen distribution in this region of the reactor, the degree of its homogeneity, and how dead zones vanish when the ring diffuser is used.

Mass transfer under bio-consumption system

Mass transfer under the bio-consumption was investigation in the current study. When all other factors affecting operation are constant, the kind and nature of the organism determines how much gas is consumed by microorganisms for metabolic operations. Based on our previous experiments with aerobic bacteria and green microalgae, the bacteria are more active than the microalgae [Razooki, et al., Al-Mashhadani et al., 2016; Ying et al., 2013]. Thus, bacteria consume more dissolved oxygen compared to microalgae. Therefore, the aerobic bacteria may be able to utilize dissolved oxygen at a concentration of 7-8 mg per liter in just a few minutes. Green microalgae, on the other hand, take longer to consume carbon dioxide. As a result, the success of the biological process is continuously

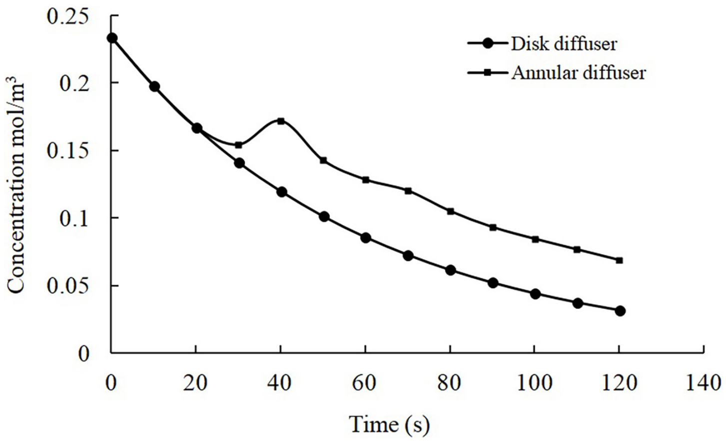

Figure 7. Concentration of dissolved oxygen in the bottom region of the two reactors equipped by annular diffuser and disc diffuser

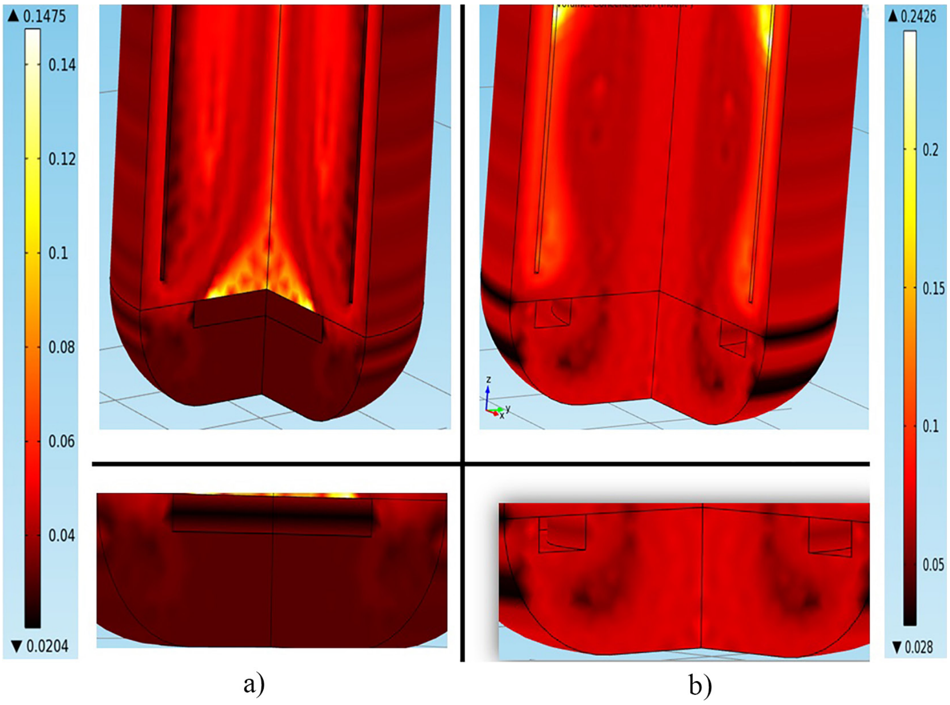

Figure 8. Oxygen concentration profile in the bottom part of bioreactor under bio-consumption process (a) disk diffuser, (b) annular diffuser

ensured by providing the bioreactor with bubble oxygen. In the current investigation, the lower part of the modified bioreactor was intended to have a substantial amount of oxygen. Thus, the suggested mathematical model incorporated bacteria (i.e equation (7)) to investigate the impact of this reactor development on the quantity of oxygen still available after biological consumption by living bacteria. The mathematical model employed in the current investigation that was timed to the aeration system incorporated the presence of microorganisms. Figure 7 and 8 display the concentration of dissolved oxygen in both bioreactors and the pertinent area of the reactor when it is consuming oxygen from the bubbling system. At the beginning of the operation, oxygen consumption by microorganisms is equal in both reactors because it was already available in the reactor. The oxygen was supplied through the downcomer region, however, the amount of oxygen supplied to this part of the reactor when using the annular diffuser is more than its amount in the conventional reactor. Therefore, the oxygen concentration is higher than that of the conventional bioreactor, which provides a second confirmation of the suggested reactor's improved performance, despite the continual consumption of dissolved oxygen by bacteria.

CONCLUSION

The investigation of dead zones produced in bioreactors was the topic of the current study. The results concluded that the internal parts of the bioreactors, as important as they are in enhancing performance, may contribute to the development and creation of heat and nutritional gradients inside the reactor. Therefore, as one of the key initiatives, the use of annular diffusers type rather than disc diffusers type was recommended in this study to be a significant step to reduce these dead areas. In both reactors, the bubble size (1×10^{-3} m to 1.6×10^{-4} m), gas mass flow (0.00698 to 0.02198 kg/(m^2.s)), and radius of the fillet (0.01, 0.02, 0.03, 0.04 m) were studied. The results showed a considerable improvement in these parameters in this region of the reactor. For instance, the average liquid velocity was measured in the suggested reactor's bottom section at 0.0198 m/s, while it was measured at 0.00077 m/s in the conventional reactor with the same bubble size. In addition, in this study, the influence of the existence of living microorganisms was taken into account in mathematical models. The results also demonstrated that, with the presence of the annular diffuser, there was more oxygen concentration left over at the bottom of the bioreactor after bio-consumption than there was in the traditional bioreactor.

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