# CFD Simulation to Study Effect of Bubble Size in Dissolved Oxygen Increase During Aeration Process

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**Abstract.** Aeration is a common process in increasing Dissolved Oxygen content in water. A common method for aeration is using large size bubbles which are commonly in the size of 4–10 mm. The simulation is intended to investigate the effect of bubble size (diameter) in oxygen transfer rate, gas hold up and increase of dissolved oxygen. Simulation was performed and validated with experimental works that were performed by Burris and Little [1]. Simulation uses mixture multiphase model for bubble-water interaction and uses multi-species model for counting oxygen transfer between bubbles and water. Simulations with bubble size of 2 and 4 mm reach saturated dissolved oxygen at 7.2 ppm and 20 s of aeration process, while the experiment obtains saturation time at 30 s and dissolved oxygen at 7.0 ppm. Bubble diameter of 1.5 and 0.9 mm have saturation time 30 s and dissolved oxygen at 5.9 ppm. Micro bubbles, ranging from 20 μm until 200 μm, have much longer saturation time and have smaller dissolved oxygen. Micro bubbles have a longer saturation time since their Buoyancy force is much smaller compared to large bubbles. Micro bubbles have saturation time ranging from 70 to 200 s. Longer saturation time indicates longer bubble's residence time and longer oxygen transfer during aeration process. It is an advantage of micro bubbles in an aeration process that usually has the depth of 10 m. The aeration process can be performed on shallow water if it uses micro bubbles.

**Keywords:** Computational Fluid Dynamics · bubble · dissolved oxygen · micro bubble · multiphase · species mass transfer

## 1 Introduction

Aeration is a common method in increasing water quality by increasing Dissolved Oxygen. Aeration using an immersed air bubble in water is a preferred method since it needs less energy in increasing contact surface between air and water. More contact surface will increase oxygen transfer rate from air bubble into liquid. Another parameter that affects transfer rate is bubble diameter and oxygen contents in the bubble. Larger bubble diameter cannot directly increase the oxygen transfer since large bubbles have much shorter contact time with liquid due to its higher buoyancy force. Some research has

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shown that small bubbles, especially for its diameter less than 1 mm, has smaller contact surface but its contact time greatly increases. Effect of contact surface and contact time between bubble and liquid can be integrated as a gas hold that is stated as a fraction of total volume of bubble and volume of liquid.

Basic characteristics of bubble dynamics (movement, breakage, aggregation, and oxygen transfer) have been studied. Burris and Little [1] performed an experiment to correlate bubble size and oxygen transfer rate on hypolimnetic (column) aerators. With bubble size ranging from 2.5 mm until 5 mm, the most significant parameter in increasing oxygen transfer rate is column depth. A deeper bubble initial position provides longer contact time with water and causes higher oxygen transfer rate. Smaller bubbles also have longer contact time since it has smaller Buoyancy force and smaller rise velocity. In general, oxygen transfer rate has proportional correlation with total surface area of bubbles immersed in liquid that is stated as gas hold up ratio, a ratio of bubble volume that is immersed in liquid with water volume.

Grund et al. [2] reported that gas hold up also depends on fluid properties of liquid, especially in its viscosity and surface tension. Gas holds up volume is also affected by bubble size. Small bubbles, 0.2 mm, have smaller bubble rise velocity. Compared to large bubbles, 2.5 mm in diameter, small bubbles have smaller bubbles rise velocity by five times.

Mohan et. al. [3] performed CFD simulation for large bubbles, ranging from 3 to 9 mm, by using the Mixture-multiphase model. Their simulations were compared to some experimental work and reported that the depth of the aerator column plays the most important rule in increasing dissolved oxygen. Wang and Wang [4] also performed CFD simulation but using bubble size ranging from 0.1 to 4 mm. The simulation uses Population Balance Model (PBM) [5] to account for bubble breakup and coalescence. The result shows that small bubbles have higher gas hold up and interfacial area. Another result shows that small and large bubbles have the same value in oxygen transfer rate from bubble into water.

Recent simulation was performed using hypolimnetic aeration as performed by Burris and Little [1] and using Mixture-multiphase model. Simulation uses initial bubble size ranging from 20 µm to 4 mm.

## 2 Simulation Equation and Model

Simulation was performed as a multiphase and multi species model using a commercial CFD software, Fluent 2021 [6]. Flow interaction between water as primary phase and bubble as secondary phase is modeled as Mixture multiphase model. The mass conservation and momentum conservation equations of the mixture was expressed as Eq. 1 and 2:

$$\frac{\partial}{\partial t}\rho_m + \nabla.(\rho_m \overrightarrow{v}_m) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\rho_m + \nabla.\left(\rho_m \overrightarrow{v}_m \overrightarrow{v}_m\right) = \nabla p + \nabla.\underline{\tau} + \rho_m \overrightarrow{g} + \overrightarrow{F} + \nabla.\left(\sum\nolimits_{k=1}^{n} \alpha_k \rho_k \overrightarrow{v}_{dr.k} \overrightarrow{v}_{dr.k}\right) \tag{2}$$

where:

$\overrightarrow{g}$ is the acceleration due to gravity ($ms^{-2}$)
$\overrightarrow{F}$ is a body force ($Nm^{-3}$)
$\alpha_k$ is volume fraction of mixture (%)
$\rho_k$ is density of the mixture components ($kg\ m^{-3}$)
$\rho_m$ is density of the mixture ($kg\ m^{-3}$)
$\overrightarrow{v}_m$ is velocity of the mixture ($ms^{-1}$)
$\overrightarrow{v}_{dr.k}$ drift velocity of the mixture components ($ms^{-1}$)

The mixture (mass-averaged) velocity $\overrightarrow{v}_m$ ($m\ s^{-1}$), the mixture density $\rho_m$ ($kg\ m^{-3}$) and the drift velocity $\overrightarrow{v}_{dr.k}$ ($m\ s^{-1}$) were expressed as Eq. 3, 4and 5:

$$\overrightarrow{v}_m = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \overrightarrow{v}_k}{\rho_m} \tag{3}$$

$$\rho_m = \sum\nolimits_{k=1}^{n} \alpha_k \rho_k \tag{4}$$

$$\overrightarrow{v}_{dr.k} = \overrightarrow{v}_k - \overrightarrow{v}_m \tag{5}$$

Along with phase interaction between bubble and water, there is species mass transfer from bubble and water. For aeration simulation, the most important species that transfer between bubbles and water is dissolved oxygen. Species transfer was expressed in Eq. 6.

$$\frac{\partial}{\partial t}(\alpha_p \rho_p) + \nabla.(\alpha_p \rho_p \overrightarrow{v}_m) = -\nabla.(\alpha_p \rho_p \overrightarrow{v}_{dr.p}) + \sum\nolimits_{q=1}^{n} (m_{pq} - m_{qp}) \tag{6}$$

where:

$m_{pq}$ ($kg\ m^{-3}\ s^{-1}$) is the mass transfer rate from primary phase to secondary phase
$m_{qp}$ ($kg\ m^{-3}\ s^{-1}$) is the mass transfer rate from secondary phase to primary phase

Since dissolved oxygen in bubbles is always higher than those in water, there is no oxygen transfer from water into bubbles ($m_{pq} = 0$).

The oxygen mass transfer from air to water was modelled using species transport equations. The local mass fraction of species (oxygen) Yi in both the phases was solved using a convection-diffusion equation Eq. 7,

$$\frac{\partial}{\partial t}\left(\rho^q \alpha^q Y^q\right) + \nabla.\left(\rho^q \alpha^q Y^q \overrightarrow{v}^q\right) = \nabla.\left(\alpha^q \overrightarrow{J}^q\right) - m_{qp} \tag{7}$$

where:

$\rho_q$ is the density of the species (oxygen) in bubble ($kg\ m^{-3}$)
$\alpha_q$ is the volume fraction of oxygen in bubble (%)
$Y^q$ is mass fraction of oxygen in buble ((%)
$\overrightarrow{v}_q$ is the velocity of oxygen in bubble ($ms^{-1}$)

$\overrightarrow{J}^{q}$ i is the diffusive flux for turbulent flow (kg $m^{-2}$ $s^{-1}$)
$m_{qp}$ is oxygen mass transfer from bubble to water (kg $m^{-3}$ $s^{-1}$)

The diffusive flux consists of laminar and turbulent effect, as shown on Eq. 8.

$$\overrightarrow{J}^{q} = -\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right)\nabla Y_i \tag{8}$$

where,

$D_{i,m}$ is the mass diffusion coefficient for oxygen in the mixture ($m^2$ $s^{-1}$),
$\mu_t$ is turbulent viscosity of fluid (Nsm$^{-2}$)
$Sc_t = \frac{\mu_q}{\rho_q D_{i,m}}$ is the turbulent Schmidt number, a mass transfer ratio between convection and molecular diffusion.

## 3 Simulation Setup

Simulation domain, water flow rate and bubble flowrate refer to Burris & Little [1], with column diameter equals to 10 m. Bubbles enter from 6 diffusers located in the bottom of the column. By using symmetric boundary conditions, simulation was performed in half of the real domain. Figure 1 shows computational domain and boundary conditions. Detailed boundary conditions are shown on Table 1. Each initial bubble size is simulated under transient conditions with time step 0.05 s and total time 40 s for large bubbles and 200 s for micro bubbles. Simulation result was saved in every 1 s.

## 4 Result and Discussion

Simulation result for initial bubble diameter 4 mm shown on Fig. 2 at simulation time 40 s. Dynamics interaction between bubble and water creates large fluctuation in water and bubble volume fraction, and mixture velocity. As a result, turbuelnt intensity of mixture increase from 5 into 63 (Fig. 2a).

Large bubble has fast dissolved oxigen saturation, where its saturation time is 20 s (Fig. 3). Highest oxygen concentration is 9.42 ppm. For a micro bubble (represented by 100 μm bubble), saturation time is 200 s. At 40 s, oxygen concentration is still far from saturation condition (Fig. 4). An interesting result appears on micro bubbles, where highest oxygen concentration is 14 ppm occuring at the tip of the diffuser. More dynamic interaction between micro bubbles and water causes high oxygen transfer rate and oxygen concentration increase.

Comparison results for all bubbles shows that large bubbles (diameter of 2 and 4 mm) have fast saturation. Compared to experiment [1], saturation time for simulation is 20 s and experiment is 30 s. Highest dissolved oxygen in simulation is 7.1 ppm, while experimental result is 7 ppm (Fig. 5). The difference is caused by inaccurate estimation of the bubble‘s interfacial area in the Mixture-multiphase model. It is recommended to use the PBM model to increase the accuracy for future simulation.

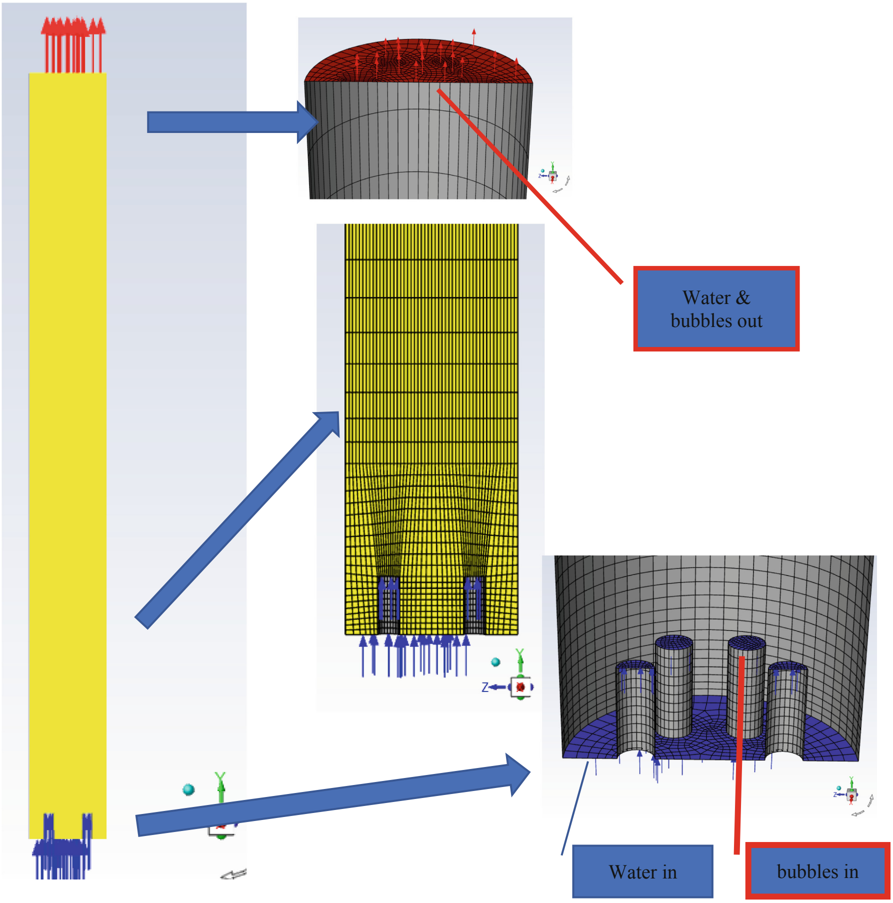
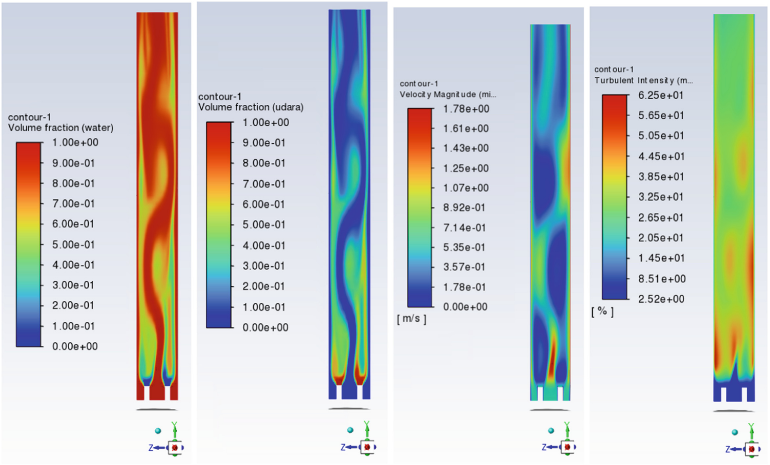


**Fig. 1.** Meshing and boundary condition for bubble simulation

**Table 1.** Boundary Conditions for simulation

| **Name** | **Value** |
|---|---|
| Buble inlet mass flow rate (kg/s) | 0.02948666 |
| Initial bubble diameter (mm) | 4.0, 2.0, 1.5, 1.0, 0.9, 0.2, 01, 0.08, 0.05 and 0.02 |
| Water inlet mass flow rate (kg/s) | 0.1544736 |
| Initial tutbulence intensity (%) | 5 |
| Initial turbulent viscosity ratio (-) | 10 |
| Pressure outlet | Atmospheric pressure (0.0 Pa (gage)) |
| Simulation type | Transient, time step = 0.05 s, total time = 40−200 s |



(a) (b) (c) (d)

**Fig. 2.** Mixture flow proterties for initial bubble diameter 4 mm and for: a) water volume fraction, b). Bubble volume fraction, c). velocity magnitude, and d) turbulence intensity

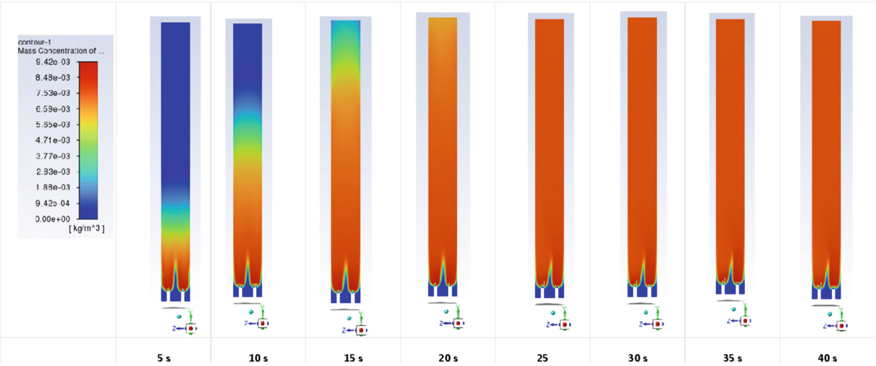


**Fig. 3.** Dissolved Oxygen contour for initial bubble diameter 4 mm.

Another interesting result is shown on micro bubbles, where smaller bubbles tend to have longer saturation time and smaller oxygen saturation. Longest saturation time is obtained in bubble diameter of 20 µm for saturation time at 200 s.

Gas holds up ratio for all bubbles are compared with experiments of Guo et. al. [7]. For a large bubble, gas holds up for simulation is 0.145 while experiment is 0.14. A smaller initial bubble has smaller gas holds up value (Fig. 6). Like dissolved oxygen, saturation in gas holds up for microbubbles much longer compared to large bubbles. Figure 7 shows saturation time for all bubble sizes. Highest time is obtained by a bubble size of 50 µm by 200 s, bubble size of 80 µm has 110 s, and bubble size of 100 µm has 70 s. Saturation time for bubble size of 1 mm or higher will have the same saturation time, namely 20 s.

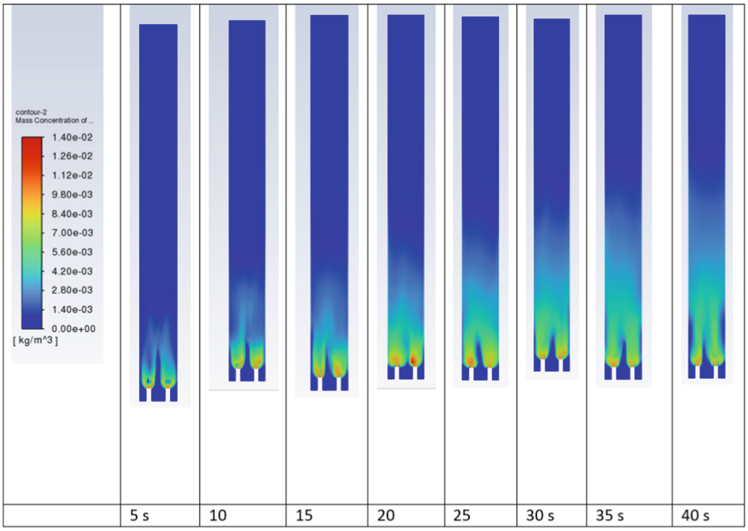


**Fig. 4.** Dissolved Oxygen contour for initial bubble diameter 100 μ

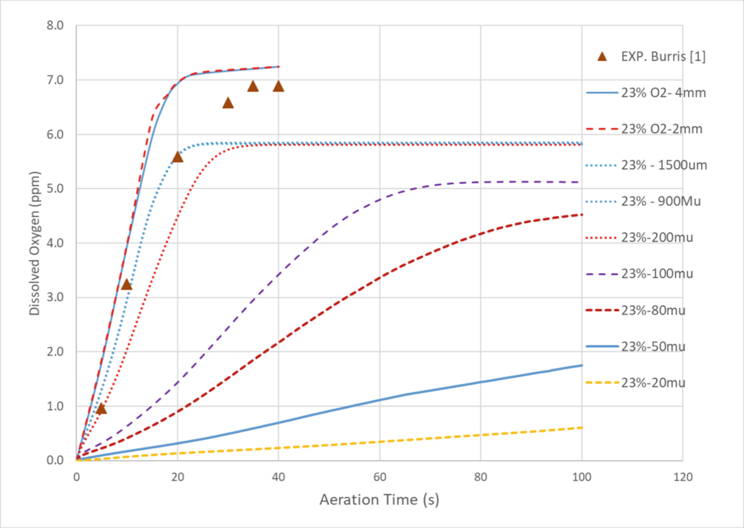


**Fig. 5.** Dissolved Oxygen saturation for various bubble diameter

Long time aeration process can be performed when the saturation time or residence time of the bubble is more than 70 s, or bubble size is 100 μm or smaller. Oxygen (mass) transfer between bubble and water can be maintained if the bubble still stays in water. Longer bubble's residence time is a useful parameter in aeration process since aeration effectiveness depends on it. A conventional aeration process requires deep water since conventional aeration uses large bubbles that have short residence time.

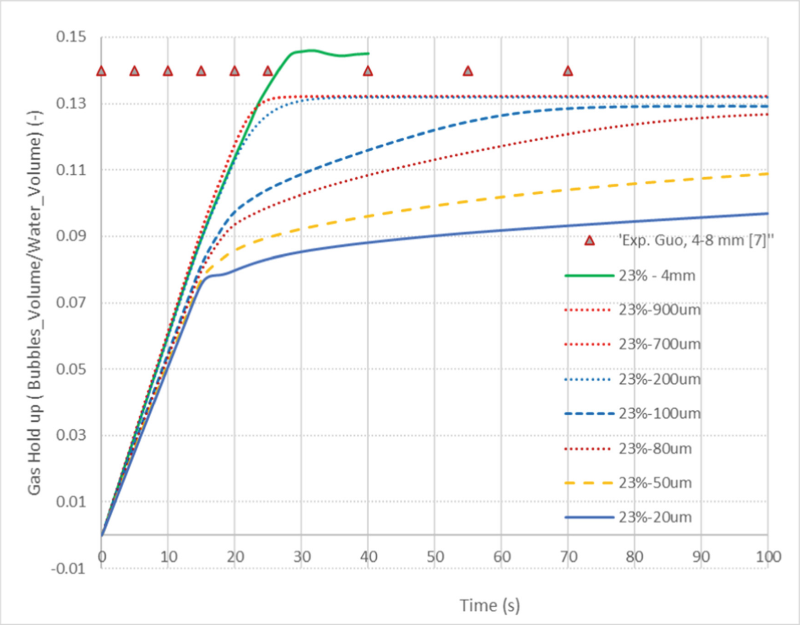


**Fig. 6.** Gas hold up for various bubble size, in transient condition

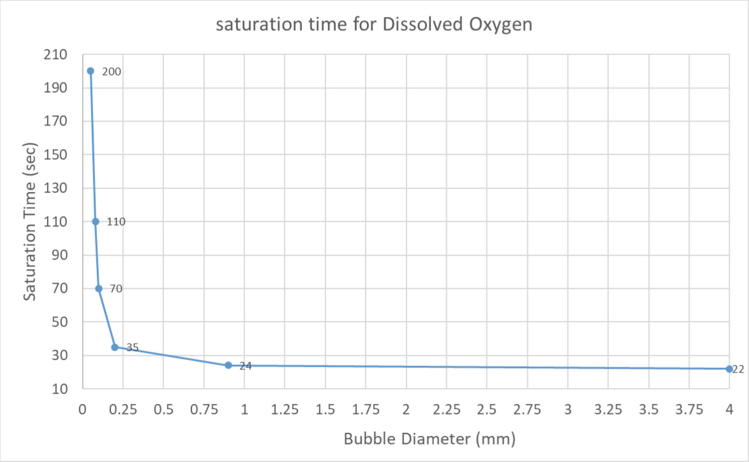


**Fig. 7.** Saturation time for various bubble size

Since microbubbles have a longer time, it can be used for aeration process more effectively. It is still possible to use micro bubbles for aeration process in shallow water, namely in water channels.

## 5 Conclusion

According to recent simulation, it can be concluded:

- Large bubble has sort saturation time and higher dissolved oxygen.
- Micro bubble with a diameter of 100 μm or smaller, has much longer residence time and gives more effective aeration process.
- Micro bubble can be used for aeration process in shallow

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