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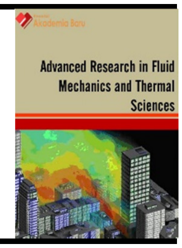

Numerical Simulation of the Attached Growth Reactor with Different Arrangement of Bio-Balls

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ABSTRACT

Two different simulations were run using ANSYS CFX to analyze the effect of aeration on the balls and to identify the effect of different arrangement on aeration. From the first simulation, close fin ball arrangement was chosen as the best arrangement because the forces acting on the surface of fin ball and inside the fin ball in this arrangement are optimum. When the forces are too low, the scouring process will not occur which promote thicker and excessive biofilm grow which will lead to clogging while when the forces acting on bio-balls are high, detachment of biofilm from the surface will occur. From the second simulation, loose fin ball arrangement and loose cage ball arrangement were chosen as the best arrangement because there is less blue contours zone which indicates the wastewater saturated faster.

1. Introduction

Attached growth processes with bio-balls or other type of bio-carriers are widely used in domestic wastewater treatment. Bio-carriers arrangement in the aeration tank is investigated in several studies to identify the optimum position [1]. Characterization of a wastewater treatment reactor is very important for design, optimization and operation of wastewater treatment systems. However, it is not possible to estimate the characterization preciously without the help of simulation. Development of wastewater treatment reactor will lead to much better understanding of the specific reactor under different conditions. Simulation is a cost effectiveness and time saving solution for researchers and developers. Many researchers are using simulation to understand the behavior of a reactor. Computational fluid dynamics (CFD) is a simulation technique being used widely in wastewater treatment study. CFD was used to predict the oxygen transfer in aeration tanks. For different volume of tanks was used to produce results of axial liquid velocities and local gas hold-ups [2]. In the other hand, activated sludge channel reactor was modeled using CFD. The simulation was run to understand the hydrodynamics, mass transfer and biological reactions of the

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reactor. The simulated results were almost close to the experimental results [3]. Immobilization of soybean seed coat for phenol removal was conducted by Rezvani et.al. They simulate a packed-bed bioreactor using CFD to understand its hydrodynamics and reaction behavior. Three different bed porosities under single-phase conditions were studied using GAMBIT. From the simulation, they were able to understand the pressure drop from for various Reynolds number and phenol removal at different inlet velocities [4]. Another study was conducted on fluidized bed reactor using CFD. Guodong Liu *et al*.,[5] studied the energy dissipation using CFD combined with Discrete Element Method (DEM). They have proved that interstitial fluid has a major role in generating energy dissipation. CFD simulation was also used to study multiphase flow behavior of a reactor. Hui *et al*., [6] studied liquid-solid-gas multiphase flow behavior of fluidized bed reactor. They used CFD to analyze the behavior of bubble in term of formation, shape and size.

Concentration polarization, fouling and scaling causes the membrane filtration to decrease its productivity by reduced flux and consuming high energy [7]. CFD is a useful tool to study the behavior of membrane system. Membrane bioreactor (MBR) was modeled through CFD simulation for cake layer fouling control in MBR. The investigation was done by optimizing MBR hydrodynamics. The model was validated by compare the simulation results and experimental results. The results showed that sludge concentration is influencing more on membrane fouling [8]. Besides that, optimization of membrane scouring and nitrogen removal was studied using CFD. An airlift external circulation membrane bioreactor was modeled for the study. The results showed that 300 mm height of gas-liquid dispersion is needed and shear stress was equalized under 1.0 m^3/h [9]. Besides that, CFD were used to understand the behavior of submerged hollow fiber membrane bioreactor. CFD simulation was focused on membrane filtration zone to study the inertial loss caused by the hollow fiber bundle with different velocities of liquid [10]. CFD has been used by Plascencia-Jatomea *et al*., [11] to study the mass transfer phenomena induced by flow velocity and flow pattern in membrane aerated biofilm reactor. They have mentioned that CFD is very useful to determine the ideal flow pattern and reactor design characteristics to produce the ideal flow. Besides that, membrane reactor was studied by Saeed Shirazian [12] for ammonia removal. CFD results showed that ammonia removal decreases at the region near the membrane inlet because the velocity at inlet is very high. Momentum heat transfer and mass transfer also can be studied using CFD in membrane reactor. Shirazi *et al*., [13] studied the hydrodynamics and effects of various spacers' geometry. They believed spacers' geometry causes the reduction in performance of membrane filtration. The CFD simulation showed fully spacer-filled feed channel for membrane filtration is not recommended as it reduces the effective membrane area and causes higher pressure drop. Mashallah Rezakazemi *et al*., [14] studied the behavior of membrane contactor using CFD linked with MATLAB. MATLAB was used to solve ammonia concentration equations of feed tank and membrane contactors since the ammonia concentrations varies with time. Results predicted concentration of ammonia correctly which helps to understand the behavior of the reactor. CFD was used to study the effect of shear stress distribution and pressure loss on membrane modules. Relationship between shear stress and membrane module was predicted using CFD simulation [7].

Clogging is one of the problem in attached growth reactor. It will affect the performance of the reactor. Type of bio-ball, carrier filling ratio, organic loading rate, aeration, hydraulic retention time and temperature can be reasons for the clogging. Many researchers have tried to reduce the clogging by manipulating the above mentioned reasons. In this paper, clogging was analyzed using CFD with different arrangement of bio-ball. Effect of bio-ball arrangement on attached growth reactor was analyzed with two different simulations. The first simulation is to analyze the effect of aeration on the balls. This was analyzed by obtaining the force acting on the surface of the ball and inside the ball. The second simulation is to identify the effect of different arrangement on aeration. This was identified by the air volume fraction contour.

2. Experimental Study

For the simulation purpose, aeration tanks and bio-balls were created using SOLIDWORKS. Three by three by three (3 x 3 x 3) arrangement was adopted instead of a single ball. Close, intermediate and loose distances were used to study how the space in between bio-balls affects the air distribution. Three different bio-balls were used in this study. They are fin ball, spike ball and cage ball. Figure 1 shows the example of tanks with three different arrangements of fin balls adopted in this study.

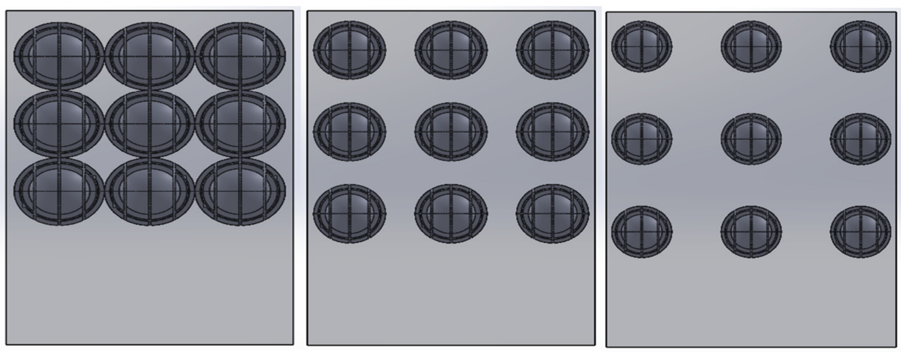


Fig. 1. Fin ball tanks

The dimensions of the tanks were tabulated in Table 1. One whole plane was assigned as diffuser for the simulation.

Table 1
Dimension of the Tanks

Bio-Balls	Dimension (Length x Width x Height) (mm)		
	Close Arrangement	**Intermediate Arrangement**	**Loose Arrangement**
Fin Ball	270 x 270 x 420	340 x 340 x 490	410 x 410 x 560
Spike Ball	300 x 300 x 388	370 x 370 x 458	440 x 440 x 528
Cage Ball	284 x 284 x 393	354 x 354 x 463	424x 424 x 533

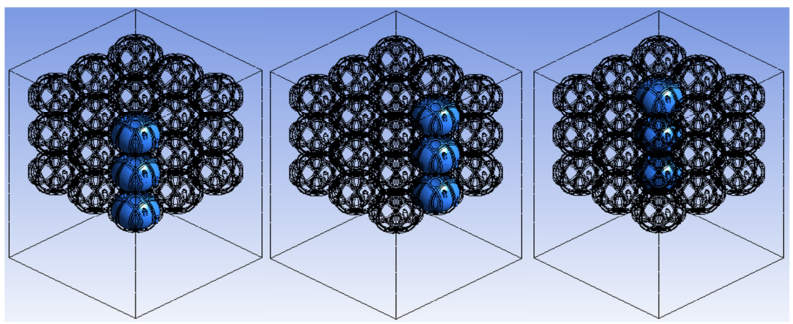
Two different simulations were run using ANSYS CFX. The first simulation is to analyze the effect of aeration on the balls. This was analyzed by obtaining the force acting on the surface of the ball and inside the ball. The second simulation is to identify the effect of different arrangement on aeration. This was identified by the air volume fraction contour. The setup in ANSYS CFX was followed as stated in previous paper [15]. Euler-Euler multiphase flow simulation was performed with finite volume method for discretization of Reynold-Averaged Navier-Stoke equations. Water (continuous phase) and air (dispersed phase) were involved in this simulation. Diameter of bubble was fixed to 3mm. Turbulence of the continuous is modelled by SST k-ω model. Turbulence of bubble modelled according to Sato and Sekoguchi [16]. Drag and buoyancy force are the main interacting forces considered in this simulation. Ishii and Zuber model was used to model the drag force. The water defined as in stagnant condition while air defined as moving from bottom to top.

At the inlet boundary, the air velocity is 1 m/s. For initial condition, the tank was specified as contain only water with no movement in any direction. A time step of 1s is used and the simulation captures at a period of 5s.

3. Results and Discussion

3.1 Effect of Aeration on Bio-Ball

In 3 x 3 x 3 arrangement, there are 27 bio-balls. The two main forces acting on the bio-balls are pressure force and viscous force. The obtained values were in Newton units. The pressure force was created by air pressure and the viscous force was generated by the viscosity of fluid occupied the domain which is water. The bio-balls were categorized as corner row carriers (A, B and C), corner middle row carriers (D, E, and F) and center row carriers (G, H and I). Only nine bio-balls were selected for analysis because identical bio-balls in term of its position were ignored. The nine chosen balls for all the three types of bio-balls with different arrangements are shown in Figure 2. The nine chosen balls were the same for all cases.



(a) (b) (c)

Fig. 2. (a) Bio-carriers A, B, C (b) Bio-carriers D, E, F (c) Bio-carriers G, H, I (Bio-Balls Chosen for Analysis)

Table 2 to 4 show the force acting on the surface and inside of nine bio-balls for different arrangements of fin ball, spike ball and cage balls obtained from ANSYS CFX post-CFD. From this simulation, the changes of force acting on the surface and inside of fin balls because of different arrangements were analyzed.

Table 2
Forces Acting on Fin Ball

Fin Ball	**Close**		**Intermediate**		**Loose**	
	Force (N)		**Force (N)**		**Force (N)**	
	Surface	**Inside**	**Surface**	**Inside**	**Surface**	**Inside**
A	0.03847	0.01949	0.02147	0.00529	0.01898	0.00095
B	0.02236	0.02280	0.01565	0.00653	0.01252	0.00382
C	0.01140	0.01732	0.01042	0.00717	0.01115	0.00254
D	0.04074	0.01761	0.02107	0.01769	0.01342	0.00694
E	0.03162	0.01095	0.01392	0.00875	0.01813	0.00843
F	0.03317	0.00837	0.00975	0.00188	0.01163	0.01555
G	0.02683	0.03376	0.01700	0.01033	0.01378	0.01555
H	0.02775	0.02049	0.01378	0.00579	0.00208	0.01550
I	0.02966	0.00548	0.01076	0.00937	0.01898	0.00095
Optimum	0.02911	0.01736	0.01487	0.00809	0.01252	0.00382

Table 3
Forces Acting on Spike Ball

Spike Ball	Close		Intermediate		Loose	
	Force (N)		Force (N)		Force (N)	
	Surface	Inside	Surface	Inside	Surface	Inside
A	0.12246	0.49741	0.09461	0.42900	0.01897	0.42533
B	0.05479	0.45247	0.06489	0.36218	0.01796	0.21227
C	0.08535	0.21673	0.03742	0.15525	0.02125	0.17469
D	0.12891	0.47155	0.04078	0.46349	0.03717	0.26193
E	0.05682	0.42316	0.03299	0.43039	0.02930	0.07308
F	0.03784	0.22158	0.04779	0.25699	0.01287	0.04169
G	0.12825	0.38531	0.05890	0.19525	0.04820	0.04169
H	0.05707	0.28042	0.03431	0.31885	0.03487	0.26168
I	0.03568	0.15019	0.05765	0.24201	0.05093	0.11135
Optimum	0.07857	0.34431	0.05215	0.31705	0.03017	0.17819

Table 4
Forces Acting on Cage Ball

Cage Ball	Close		Intermediate		Loose	
	Force (N)		Force (N)		Force (N)	
	Surface	Inside	Surface	Inside	Surface	Inside
A	0.00502	0.00010	0.00166	0.00029	0.00315	0.00018
B	0.00188	0.00015	0.00077	0.00025	0.00465	0.00004
C	0.00096	0.00047	0.00032	0.00022	0.00121	0.00033
D	0.00548	0.00008	0.00202	0.00021	0.00442	0.00034
E	0.00229	0.00029	0.00115	0.00046	0.00633	0.00043
F	0.00185	0.00073	0.00125	0.00010	0.00574	0.00251
G	0.00530	0.00011	0.00365	0.00080	0.00695	0.00149
H	0.00249	0.00022	0.00230	0.00017	0.00263	0.00046
I	0.00176	0.00053	0.00240	0.00033	0.00584	0.00222
Optimum	0.00502	0.00010	0.00172	0.00031	0.00455	0.00089

Figure 3 and 4 show the graphs of force acting on the surface and inside of three types of bio-balls with three different arrangements. The simulation was run with aeration velocity of 1 m/s. The forces acting on the bio-balls are pressure force and viscous force. Pressure force is induced from air pressure by aeration while viscous force is induced by the viscosity of fluid occupied the domain which is water. In order to control the clogging issue, optimum force is very important as well as to have healthy biofilm growth. Biofilm becomes heterogeneous, porous and weaker when the force is too weak [17].

Based on the Figure 3, the forces acting on the bio-balls in cage ball arrangements are lower compared to fin ball and spike ball arrangements. When the forces are too low, the scouring process will not occur. Therefore, thicker and excessive biofilm will grow on the surface of cage ball which eventually will lead to clogging. As the main concern of the study is to avoid clogging, cage ball arrangements cannot be chosen as the best arrangement. Besides that, the forces acting on the bio-balls in spike ball arrangements are high compared to cage ball and fin ball arrangements. When the forces acting on the surface of bio-balls is high, the detachment of biofilm from the surface will happen. This will decrease the efficiency of attached growth process as biofilm growth plays the main role in wastewater treatment. Therefore, fin ball arrangements were chosen as the best arrangements because the forces acting on the surface of bio-balls in fin ball arrangements are optimum.

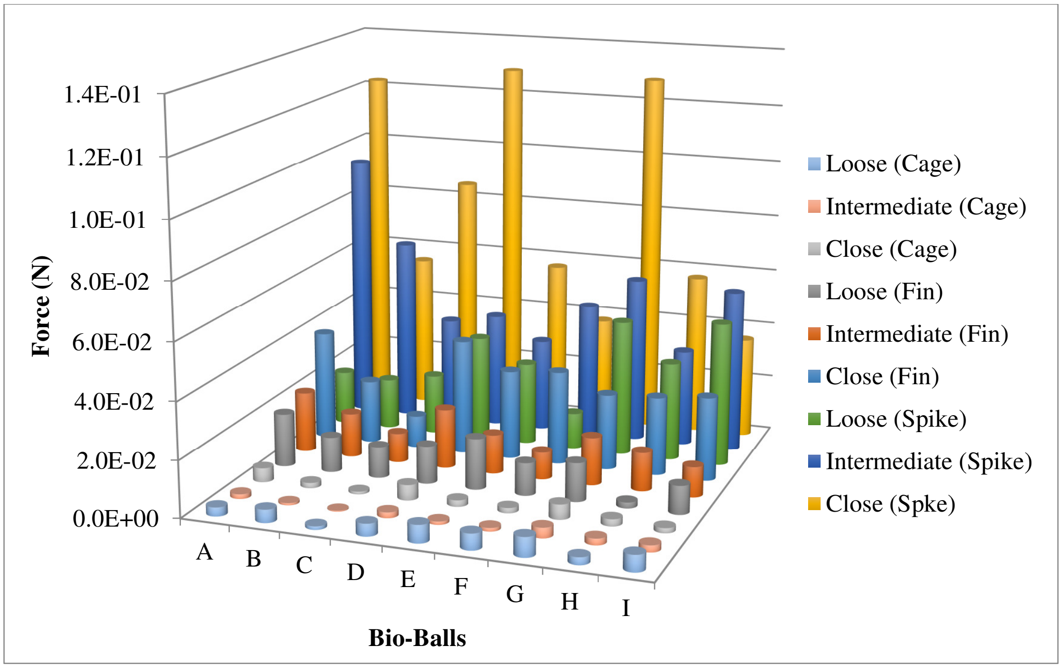


Fig. 3. 3-D Graph of Force acting on the Surface of Different Bio-balls with Different Arrangement

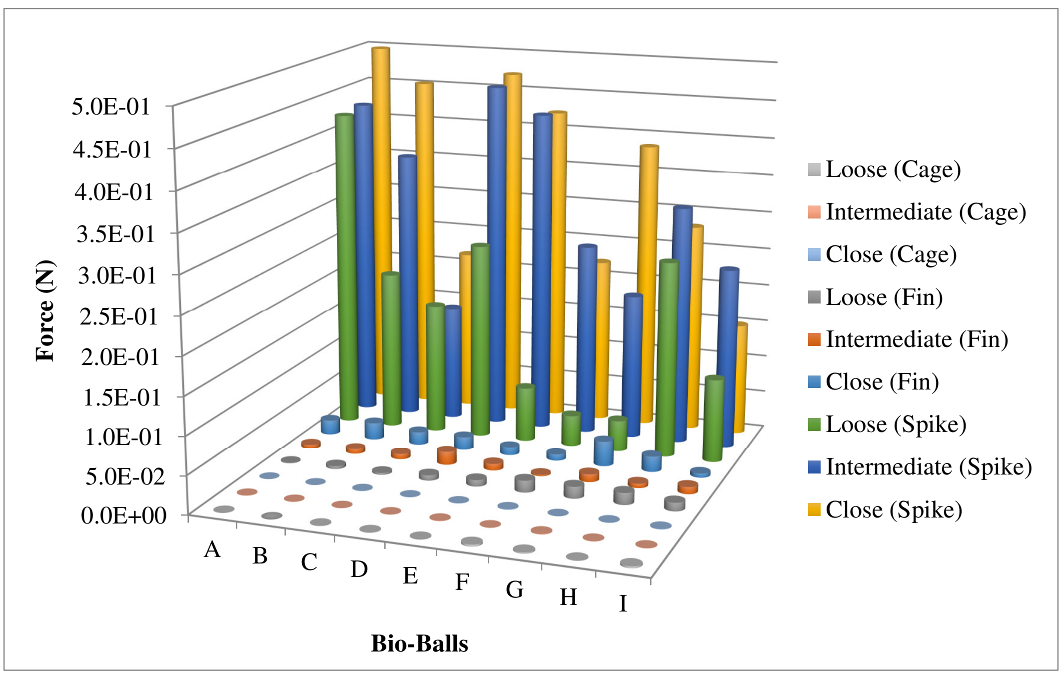


Fig. 4. 3-D Graph of Force acting inside of Different Bio-balls with Different Arrangements

Next, from Figure 4, the forces acting inside the bio-balls in cage ball arrangements are lower compared to fin ball and spike ball arrangements. Besides that, the forces acting inside the bio-balls in spike ball arrangements are higher compared to fin ball and cage ball arrangements. As discussed earlier, the forces acting inside the bio-balls cannot be too high or too low. Therefore fin ball arrangements were chosen again as best arrangements because the forces acting inside the bio-balls of fin ball arrangements are optimum.

Finally, the analysis was done on the three fin ball arrangements to identify the best among the three different arrangements of fin ball. The same discussion pattern that was used previously was followed. The best arrangement was chosen based on the optimum force acting on the bio-balls. The close fin ball arrangement was chosen as the best because of the forces acting on it. The forces acting inside the intermediate and loose fin ball arrangements are very low which will lead to excessive biofilm growth inside the fin ball. The forces acting on the fin ball is also needed to be optimum to avoid clogging inside of the bio-ball. This is the reason why the close fin ball arrangement was chosen as the best arrangement even though the forces acting on the surface is high compared to the other two arrangements of fin ball. In order to control the clogging issue, optimum force is very important as well as to have healthy biofilm growth. Biofilm becomes heterogeneous, porous and weaker when the force is too weak [17].

3.2 Effect of Arrangement on Air Distribution

Figure 5 to 7 show the air volume fraction contours of three different arrangements of fin ball, spike ball and cage ball at 5 s respectively. The best arrangements will be identified based on the dead zones. The better the air distribution, the better the arrangement will be.

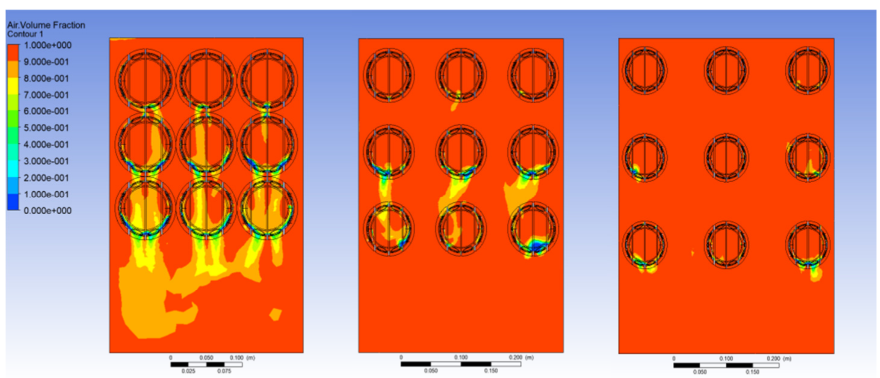


Fig. 5. Air Volume Fraction Contours of Three Different Fin Ball Arrangements at 5 s

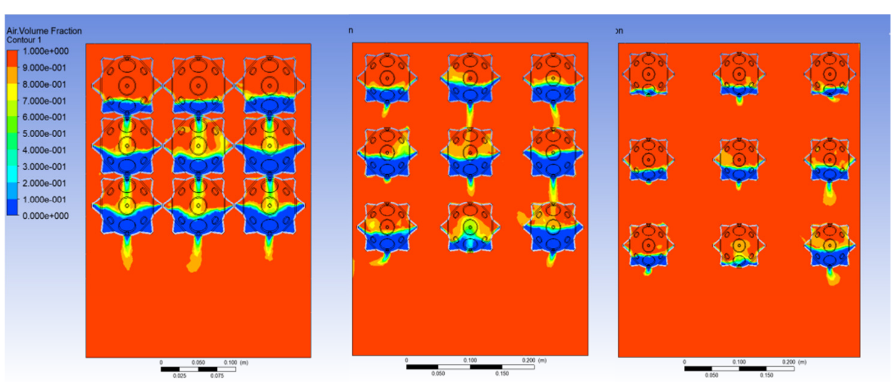


Fig. 6. Air Volume Fraction Contours of Three Different Spike Ball Arrangements at 5 s

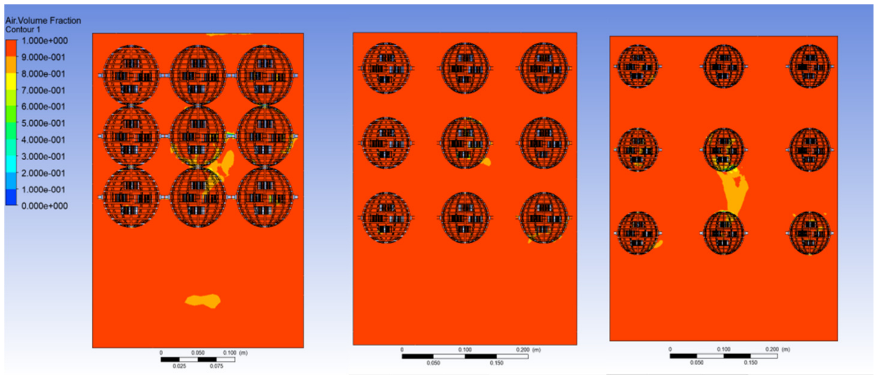


Fig.7. Air Volume Fraction Contours of Three Different Cage Ball Arrangements at 5 s

Wastewater needs to be saturated with oxygen for having a microbial activity. The faster the wastewater saturated with oxygen, the energy consumed by aeration can be reduced. This will also reduce the cost involving in operating the attached growth process. Air volume fraction shows the volume of air covered the total domain. Air volume fraction can be calculated by divide the volume of air with the total volume. The value of air volume fraction varies from one to zero with the interval of 0.1. Air volume fraction with value one indicates that the volume of air and total volume is same while air volume fraction with value zero indicates that the volume of air is zero. The color range for air volume fraction is from blue to red. Blue indicates the oxygen saturation is very less while red indicates the oxygen saturation is very high. Therefore, from the air volume fraction, saturation of oxygen in wastewater can be measured.

From the figures above, more area of blue contours can be seen in close arrangement of spike ball while loose arrangement of cage ball and fin ball has the least area of blue contours. Blue contours indicate the minimum air volume fraction which means the presence of oxygen is less in that area. Minimum air volume fraction will result in poor bacterial growth along this area. Besides that, the energy consumption by aeration can be reduced by reducing the aeration operating hours. Therefore, the loose fin ball and cage ball arrangement is the best arrangement in order to have better biofilm growth. Besides that, better biofilm growth will increase the efficiency of attached growth process. From this, it's clearly understood that the wider that gap between bio-balls the better the oxygen saturation. Oxygen saturation is very poor in spike ball arrangements because the area of blue contours which indicates the minimum air volume fraction is bigger. From the first simulation, the force acting inside the spike ball arrangements were highest compared to fin ball arrangements and cage ball arrangements. Although higher forces are acting inside the bio-balls of spike ball arrangements, the force is not uniformly distributed all over the area. That can be clearly seen in the air volume fraction contour where a lot of areas are blue in color which is not fully aerated or has minimum air volume fraction. In contrast, there is no blue contours zone in cage ball and fin ball arrangements. Therefore, cage ball arrangement and fin ball arrangement can be considered as the best arrangements in term of oxygen saturation. Besides that, aeration operating hours can be reduced which will reduce the energy consumption of the attached growth process too.

4. Conclusion

The main objective is to analyze the dynamic path across bio-balls. CFD simulation was done using ANSYS CFX software. Two types of simulations were done to investigate this objective. The first simulation is to analyze the effect of aeration on the bio-balls. This was analyzed by obtaining the force acting on the surface of the ball and inside the ball. The second simulation is to identify the effect of different arrangement on aeration. This was identified by the air volume fraction contour obtained from ANSYS CFX software.

From the analysis of effect of aeration on the bio-balls, close fin ball arrangement was chosen as the best arrangement. Close fin ball arrangement was chosen because the forces acting on the surface of fin ball and inside the fin ball in this arrangement are optimum. When the forces are too low, the scouring process will not occur. Therefore, thicker and excessive biofilm will grow on the surface of cage ball which eventually will lead to clogging. When the forces acting on bio-balls are high, detachment of biofilm from the surface will occur. This will decrease the efficiency of attached growth process as biofilm growth plays the main role in wastewater treatment. In order to control the clogging issue, optimum force is very important as well as to have healthy biofilm growth. Biofilm becomes heterogeneous, porous and weaker when the force is too weak [17].

Besides that, from the analysis of effect different arrangement on aeration, loose fin ball arrangement and loose cage ball arrangement were chosen as the best arrangement. Wastewater needs to be saturated with oxygen for have a microbial activity. The faster the wastewater saturated with oxygen, the energy consumed by aeration can be reduced. This will also reduce the cost involving in operating the attached growth process. There is no blue contours zone in cage ball and fin ball arrangements. Blue contours indicate the minimum air volume fraction which means presence of oxygen is less in that area. Minimum air volume fraction will result in poor bacterial growth along this area. Therefore, loose cage ball arrangement and loose fin ball arrangement can be considered as the best arrangements in term of oxygen saturation. Besides that, aeration operating hours can be reduced if the oxygen saturation is faster which will reduce the energy consumption of the attached growth process too.

In conclusion, close fin ball arrangement was chosen as best from the analysis of effect of aeration on bio-ball simulation. In the next simulation, loose cage ball and fin ball arrangements were chosen as best arrangement. At the end of study, one best arrangement needs to be chosen. Cage ball arrangements were the worst arrangement in the analysis of effect of aeration on bio-ball simulation. This is because the force acting on the cage ball arrangements are very low. This will lead to clogging because excessive and thicker biofilm will grow if the force is low. In that case, loose cage ball arrangement that were chosen from the analysis of effect of arrangement on air distribution cannot be the best arrangement. In addition, the force acting inside the loose fin ball is low and the oxygen saturation is better which will promote clogging inside the bio-ball from this arrangement. Therefore, close fin ball arrangement is chosen as the best arrangement and also the oxygen saturation is not poor as compared to spike ball arrangements. This arrangement was chosen because of better oxygen saturation and optimum force acting on the surface and inside the fin ball.

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