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Impact of Rotational Speed and Oxygen Flow Rate on Homogeneity and Fluid Flow Patterns Using a CFD-Based Side Entry Mixer in the Aeration Process

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Abstract
Mixing is an essential operation in many industrial processes to ensure uniform material distribution and enhance mass transfer. A side-entry mixer (SEM) is widely used in large storage tanks because it provides effective circulation with lower installation and maintenance costs than conventional top-entry mixers. This study investigated the effects of impeller rotational speed and oxygen flow rate on the homogeneity and flow patterns of a calcium carbonate ($CaCO_3$)–water suspension during the aeration process. Computational Fluid Dynamics (CFD) simulations using ANSYS and experimental visualization were employed to evaluate mixing performance. The operating conditions included impeller rotational speeds of 500, 600, 800, 1000, and 1200 rpm and oxygen flow rates of 5, 10, 15, 20, and 25 L/s. The results showed that increasing rotational speed and oxygen flow rate accelerated mixing and improved fluid homogeneity. The flow was dominated by axial and combined axial–radial patterns, promoting uniform circulation throughout the tank. Under the investigated conditions, the best mixing performance was achieved at 1200 rpm with oxygen flow rates of 20 and 25 L/s, reaching complete mixing within 40 s. Higher Reynolds and Sherwood numbers at these conditions also indicated enhanced turbulent mixing and mass transfer.

Keywords: Homogeneity; Mixing; Rotational Speed; Oxygen Flow Rate

1 Introduction

The mixing process is a very important process and is often found in large and small industries. In the mixing process, most of the products produced can be processed and mixed with other materials. The machine used for this mixing process is usually called a mixer. When viewed from its own function, the mixer can be classified as a processing machine. A processing machine is a machine used to carry out the processing process. Along with the development of modern technology today, humans are greatly facilitated by the existence of various equipment that has been created and can be operated and used automatically. Mixing machines for processing have also been developed in both large and small industries. The design of a mixer

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machine requires analysis and calculation of component strength. The components that need to be considered are the oxygen flow rate, In impeller blade and stirrer speed [1].

Stirred tanks with side entry mixers are widely used in the pulp and paper industry, aeration, petroleum industry, and as biodigesters in biogas plants. These agitators provide robust reliability, versatility of application, and easy and economical installation, operation and maintenance. The main features of stirred tanks with side entry mixers are large tank size, with small impeller diameter. The ratio of impeller diameter to tank diameter is relatively small compared to stirred tanks with top entry mixers [2]. The type of agitator used depends on the desired process results, process requirements, and the scale or volume of material to be processed. The biggest advantage of the type of agitator used in the mixing process using side-entry stirred tanks is to produce axial flow, because the desired flow pushes the fluid toward the front of the impeller shaft, allowing the fluid to circulate throughout the tank after colliding with the tank wall [2].

Aeration in a side entry mixer system is influenced by the rotational speed and oxygen flow rate, which impacts the flow pattern and mixing homogeneity. Based on research by Karimi et al. (2013), biochemical processes often experience a lack of oxygen supply, so high mixing efficiency is required. Impellers play an important role in mixing, solids suspension, and enhancing oxygen transfer by expanding the gas-liquid interfacial area. This study tested three types of impellers (Rushton, Pitched Blade 4-blade, and 2-blade) at speeds of 0-1000 rpm and oxygen rates of 1-5 L/min. Results showed that increasing the stirring speed, especially at 400- 800 rpm, greatly increased the KLa value. Although increasing the air rate also increased the KLa, the effect of stirring speed was more dominant. The best configuration was found to be the twin Rushton turbine, which increased the KLa by 50-77% compared to other impellers. The combination of 400-800 rpm and 3-5 L/min aeration with twin Rushton is suggested as the optimal condition for oxygen transfer efficiency in the bioreactor [3].

While from previous research related to speed is the same as the research of Zhao et al. (2024) used numerical simulation to study gas-liquid two-phase flow in a pressurized leaching tank with a top entry mixer. The variables tested included air entry velocity, sulfuric acid concentration, and the presence of baffles, with high turbulent stirring conditions ($Re = 9.2 \times 10^4$). Results showed that increasing the air velocity from 0.05 m/s to 0.45 m/s significantly increased the gas holdup from 0.18% to 12.06%. The addition of baffles also improved the gas distribution efficiency although it only increased the gas holdup by about 2%, but with very little power consumption (~1.2%). A higher concentration of sulfuric acid increases the viscosity, slows down the rise of bubbles, and contributes to the increase in gas holdup. Optimal conditions were obtained at an air velocity of 0.45 m/s, the presence of baffles, and turbulent flow to maximize oxygen distribution and reaction efficiency [4].

In this study, we propose related factors of rotational speed and oxygen levels to stirring using the CFD or Computational Fluid Dynamics method and visualization. In the rotational speed factor, we use rpm variables of 500,600,800,1000,1200 Rpm and with oxygen of 5,10,15,20,25 L/S. The process of adding oxygen is an effort to reduce pollutants in water so that the concentration of pollutants will decrease or disappear completely. The addition of oxygen can be done by inserting air into porous waste or nozzles placed in the middle or bottom of the aeration tank and will increase the speed of contact of the air bubbles with the waste so that the oxygen supply process runs faster, and forces the water up to contact with oxygen through the rotation of the propeller placed on the surface of the wastewater which causes the wastewater to be lifted up so that there is direct contact with the surrounding air [5]. Aeration is the addition of oxygen to water so that the dissolved oxygen in the water is higher. In principle, aeration mixes water with air or other materials so that low-oxygen water meets oxygen or air. The effectiveness of aeration depends on how much of the water surface is in direct contact with the air [6].

However, previous studies mainly investigated top-entry mixers or focused on oxygen transfer performance without evaluating the combined influence of impeller rotational speed and oxygen flow rate on flow patterns and mixing homogeneity in side-entry mixers. In addition, studies integrating CFD simulation with experimental visualization remain limited. Therefore, this study investigates the effects of impeller rotational speed and oxygen flow rate on the flow pattern and mixing homogeneity of a water–calcium carbonate ($CaCO_3$) suspension under oxygen aeration using a side-entry mixer. CFD simulations were complemented by experimental flow visualization using chia seeds as tracer particles to compare the observed flow behavior with the numerical predictions.

2 Materials and Methods

The fluid flow inside the side-entry mixer was simulated using ANSYS Fluent 16.0. The three-dimensional geometry of the mixing tank and impeller was developed based on the dimensions of the laboratory-scale experimental apparatus to ensure consistency between the numerical simulation and experimental visualization. The simulation was conducted to evaluate the effects of impeller rotational speed and oxygen flow rate on flow patterns and mixing homogeneity during the aeration process.

The model consisted of a cylindrical mixing tank equipped with a side-entry impeller and an oxygen inlet used during the aeration process. The computational domain was divided into a stationary zone representing the tank and a rotating (moving) zone surrounding the impeller to accurately simulate the impeller motion.

The computational domain was discretized using an unstructured tetrahedral mesh. A finer mesh was applied within the moving zone surrounding the impeller and oxygen inlet to accurately capture the velocity gradients and turbulent flow generated during mixing, whereas a coarser mesh was applied in the stationary zone to reduce computational cost.

The mesh was generated using a minimum element size of 0.002 m, a maximum element size of 0.016 m, and a growth rate of 1.1999 with curvature and proximity size functions. The simulations were performed using a transient pressure-based solver. Water was defined as the primary phase and oxygen as the secondary phase using the Volume of Fluid (VOF) model. Pressure–velocity coupling was solved using the PISO algorithm, and hybrid initialization was applied prior to each simulation. The tank walls were treated as stationary no-slip walls, while the impeller rotation was prescribed according to the selected rotational speed. Oxygen was introduced through the diffuser at the specified oxygen flow rates to simulate the aeration process.

The realizable k–ε model was selected because it offers improved prediction of recirculation and flow separation in turbulent rotating flows compared with the standard k–ε model, while maintaining lower computational cost than more advanced turbulence models. Therefore, the realizable *k–ε* model was considered appropriate for predicting the turbulent flow field and mixing characteristics in the present side-entry mixer [7] [8].

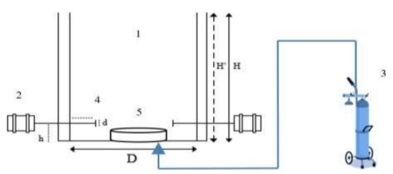
To determine homogenization in the homogeneity method in CFD, it can be done by calculating the concentration or density of the 3 sample points, which when the 3 samples are close, it can be said to be homogeneous. For steps using CFD on homogenization, namely input geometry to Ansys then set the geometry, the second step is to enter the mesh to name the tank, the third step is to enter the setup to enter the material and the variables used, namely oxygen and rotational speed, the fourth step after that can be run and produce the desired results. The results obtained are based on mixing using density differences, which at each point have a different density because $CaCO_3$ is inserted and mixing occurs from settling to lifting, until it is completely mixed, perfect mixing will produce a thick blue color and indicate that the density is close to the same.

The following method is the same when you want to know the flow pattern, only the difference is that if the homogeneity of the material is three (water, oxygen, and $CaCO_3$) while for the flow pattern there is only oxygen and water.

Table. 1. Material Properties

Water		
Density	997	kg/m3
Molar Mass	18,01	g/mol

$CaCO_3$		
Density	2711	kg/m3
Molar Mass	100,0869	g/mol
Solubility in Water	0,0013	g/100mL
Oxygen		
Density	960	kg/m^3
Molar Mass	50	g/mol



Description :

1. Tank side entry mixer
2. Impeller driving mechine
3. Oxygen
4. Impeller propeller
5. Difusser

Figure 1. Side Entry Mixer 2D dan D3

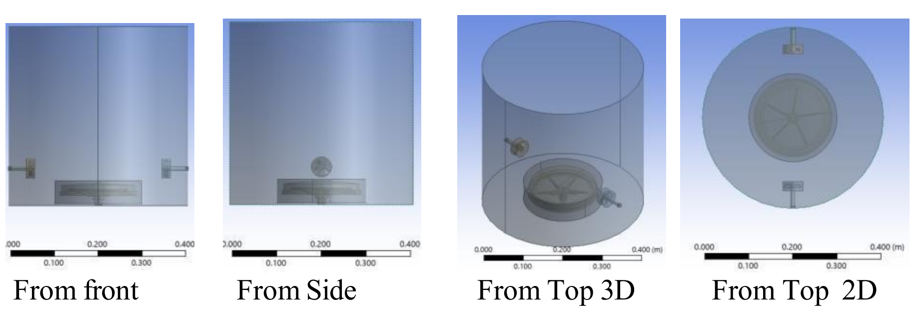


Figure 2. Side Entry Mixer Geometry

Mixing processes on an industrial scale typically use high rotational speeds of 500, 600, 800, 1000, and 1200 RPM. Also, oxygen rate 5, 10, 15, 20, and 25 liter/second. By making the rotation variable and adding oxygen to the aeration process will help the mixing process to speed up the homogenization process.

3 Results and Discussion

The purpose of this study is to determine the effect of variations in oxygen addition and mixer rotation speed on fluid flow patterns with a Side Entry Mixer using Computational Fluid Dynamics (CFD) methods. To determine the mixing time under the influence of variation of oxygen rate and mixer rotation speed on fluid homogeneity in the Side Entry Mixer.

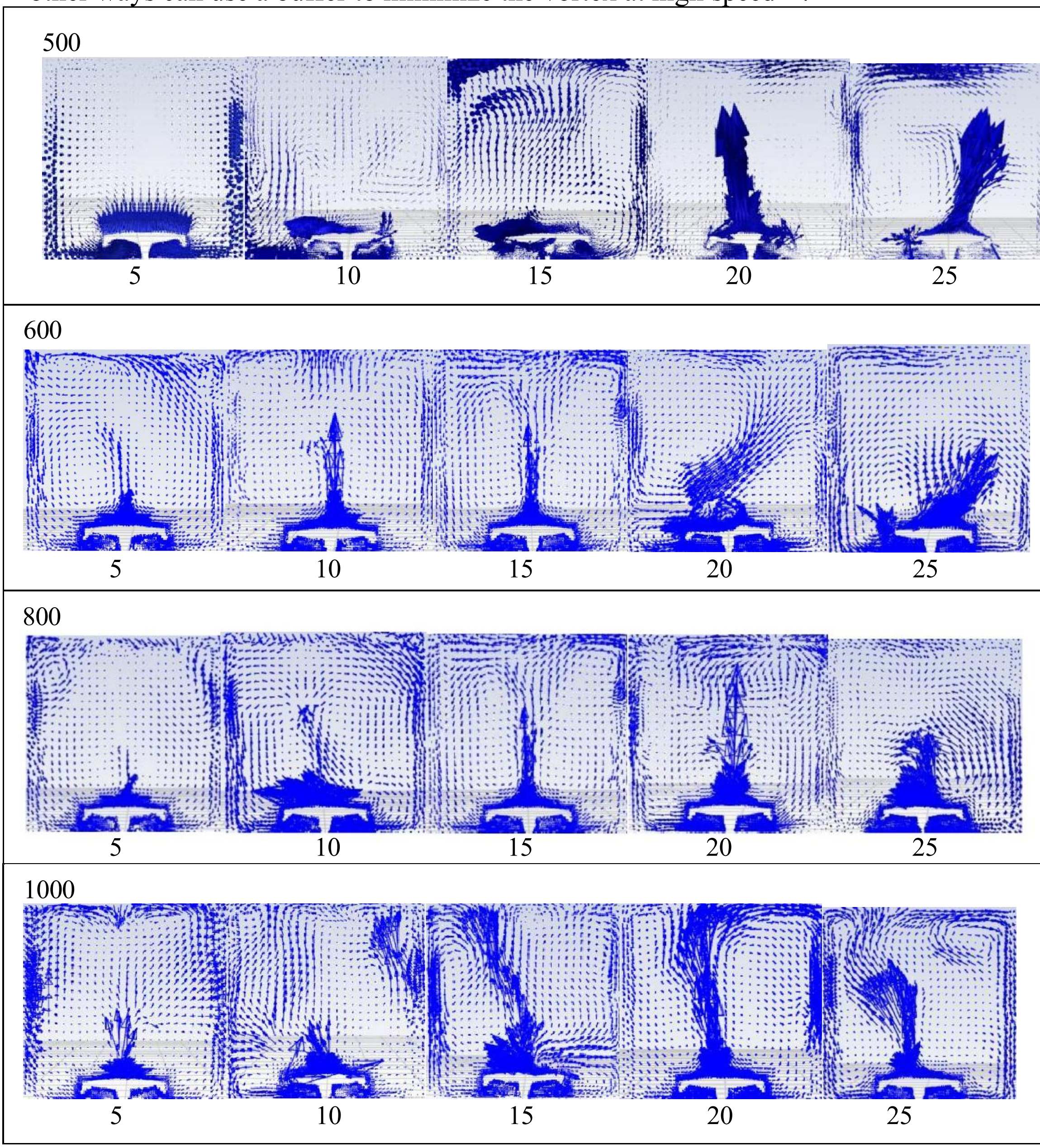
3.1 Effect of Flow Pattern

Figure 3 Based on the results, the flow pattern formed was mainly axial, with some areas showing a mix of axial and radial flow. The flow pattern observations were made at the same time, specifically at the 10th second. At 500 to 600 RPM, for all oxygen flow rate variations, the flow appeared to be axial. Meanwhile, at 800 to 1200 RPM, for all oxygen flow rate variations, the flow pattern became a combination of radial and axial flow according to the CFD results. And also there no vortex around the alligator.

Vortex flow which is also known as pulsating flow or eddy can occur in various fluids such as water, oil, air. Vortex flow is considered a disadvantage in fluid flow even though there are advantages. Vortex flow is a water flow that rotates with streamlines forming concentric circles. The vortex movement is caused by the difference in speed between adjacent fluid layers. It can also be interpreted as the natural motion of the fluid caused by speed and pressure parameters. Vortex as a vortex which is the effect of rotational rotation where viscosity has an effect in it. From the definition above, it can be assumed that in stirring the size of the vortex can be seen from the impeller rotation: The impeller rotates the fluid which causes the layer of fluid near the impeller to move quickly, while the layer further away is slower, so a difference in speed will appear. Centrifugal pressure: The fluid is pushed outward due to centrifugal force, then forms a downward vortex. Fluid viscosity: If the fluid is thin (low viscosity, water), vortexes are easily formed and if the fluid is thick (high viscosity, honey), vortexes are difficult to form because the fluid tends to be resistant to movement. But in the results, we studied there was no vortex because it used a side entry mixer, different from when the top mixer [9].

In previous research (Iman Pradana A. Assagaf, 2024) which examined the Numerical Study of the Effect of Axial Flow on Turbulent Taylor Vortex Flow with Heat Transfer which wants turbulent flow in Taylor-Couette flow with axial flow is characterized by a complex and irregular vortex structure. This is in accordance with the results obtained that the vortex is irregular due to the faster speed. This vortex is formed due to the interaction between the shear force generated by the rotation of the inner cylinder and the inertial force of the fluid. The higher the rotation of the inner cylinder, the more energy is put into the system. This causes the vortices to become smaller, more numerous, and the interactions between the vortices to become more intense, resulting in a more complex flow [10].

Based on the above results from our research, namely forming mix axial and radial on CFD, also no vortex or air space. This is because we use a side entry mixer and not a top entry mixer, because if you use a top entry mixer it will produce a large enough vortex according to the speed of rotation, where the weaker the rotation the vortex will be large, and when the rotation is tightened the vortex will decrease, and other ways can use a buffer to minimize the vortex at high speed [4].



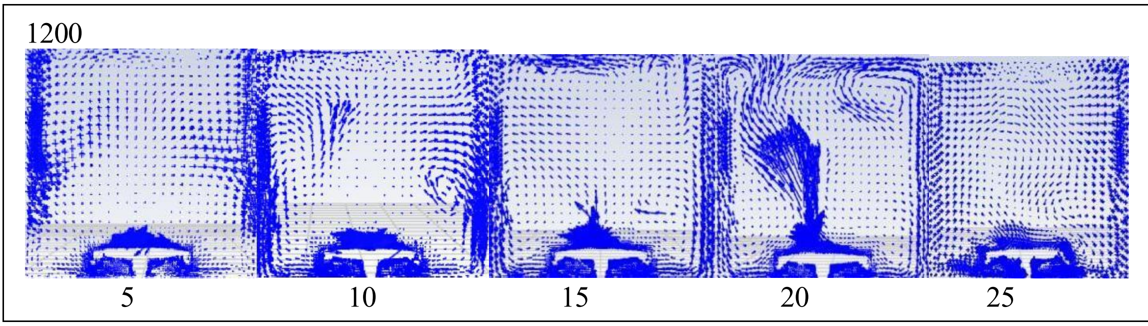


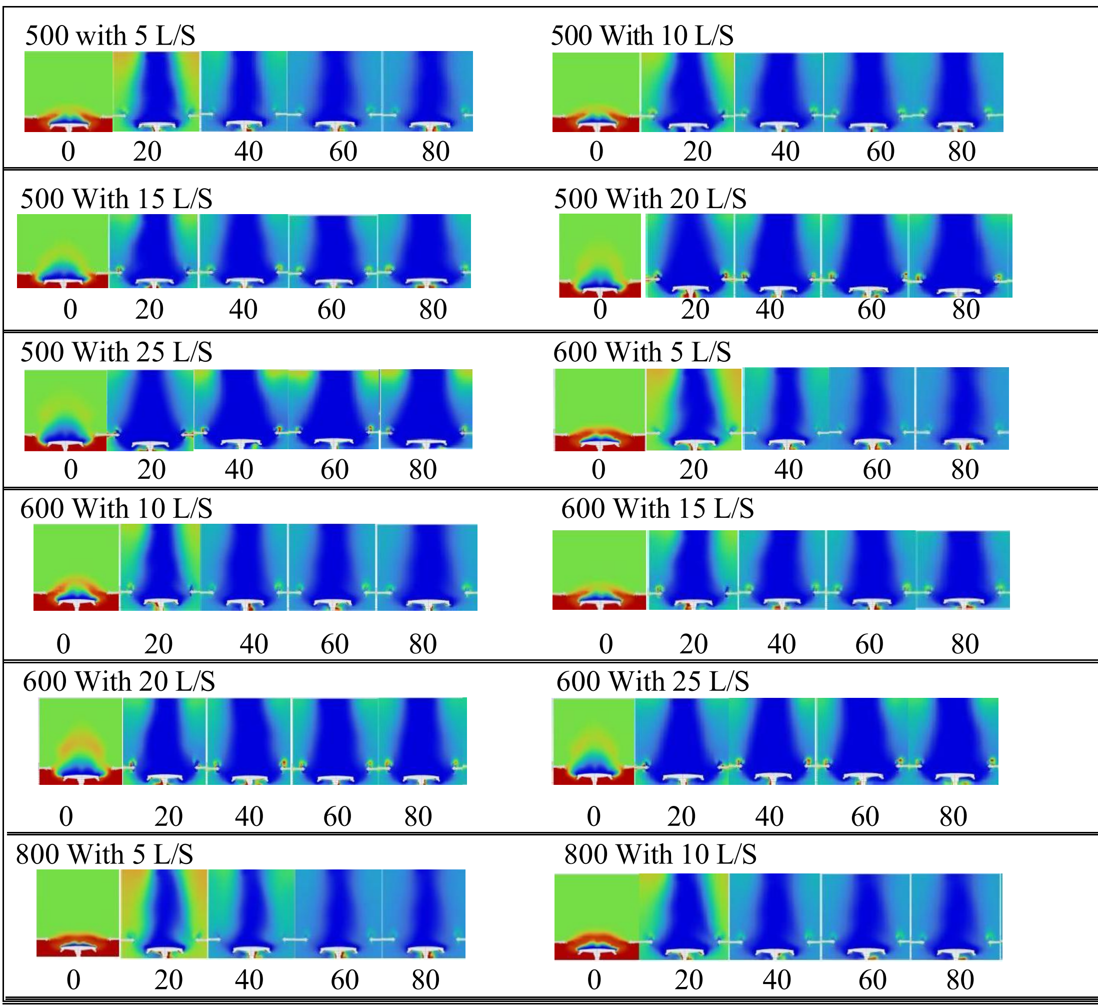
Figure 3. Flow Patterns

3.2 Effect of Homogenity

Figure 4 above is the result of the homogeneity distribution contour of each variable, where the rotating speed and oxygen input affect the homogeneity acceleration. Rotary speed Stirring (mixing) is an activity of mixing operations between two or more substances to obtain a homogeneous mixture. The existence of stirring aims to accelerate the fluid mixing process because it can accelerate the transfer of mass and energy in the form of heat, whether accompanied by chemical reactions or not, and to reduce inequality of conditions, temperature, or other properties in a material. In addition, stirring can also prevent precipitation [11]. A high level of homogeneity is influenced by factors such as mixing time and speed. High homogeneity reflects an even distribution of material, which is an important condition for improving the quality of aeration. An efficient mixing process requires optimal duration and speed so that the reactant molecules can interact intensively and the flow will be homogenous [12].

Based on previous research Imron, 2020 with the title Simulation of Palm Oil Mill Wastewater Mixing Homogeneity and Its Effect on Preliminary Treatment in the Sei Pagar Biogas Pilot Plant Equalization Pond, it was found that 10 seconds was a homogeneous result. From the contour it can be observed that as time goes by, the zone that has velocity (non-zero velocity) will spread more and more. At the 10th second almost the entire pool space already has a velocity value of more than zero. This indicates that every fluid particle is moving and circulating. In the biogas pretreatment process from POME, it is very important to prepare ideal conditions before entering the biodigester reactor. The main parameters for the success of the biogas production process include pH, temperature, and homogeneity of the substrate mixing. Homogeneity of the substrate can be achieved by a stirring or agitation system in the pretreatment process and in the biodigester reactor. The effect of stirring on the growth of microorganisms is quite significant. The higher the stirring rate, the higher the volatile suspended solids (VSS) content. This indicates that the number of microbes increases as the stirring rate increases. The evaluation of the design of the agitator for the equalization pond concluded that the design of the agitator using a turbine blade pitch impeller type can achieve homogeneous fluid mixing conditions in a fairly short time, i.e. at times above 10 seconds excellent homogeneity has been achieved in both the axial and radial directions using a top entry mixer[13].

Based on the results obtained from the variable speeds of 500, 600, 800, 1000, and 1200 with oxygen velocities of 5, 10, 15, 20, and 5 liters/second, it is found that the faster the speed and the more homogeneous oxygen is in accordance with the literature above. It can be seen that the results with oxygen speeds of 20 and 25 are the best in color and close to blue at the top, namely at speeds of 1000 and 1200, because at the same speed and the same oxygen the top color is not close to blue and at speeds of 1000 to 1200 the blue color is consistent from oxygen 5 to 25 liters/second with a time of 40 seconds.



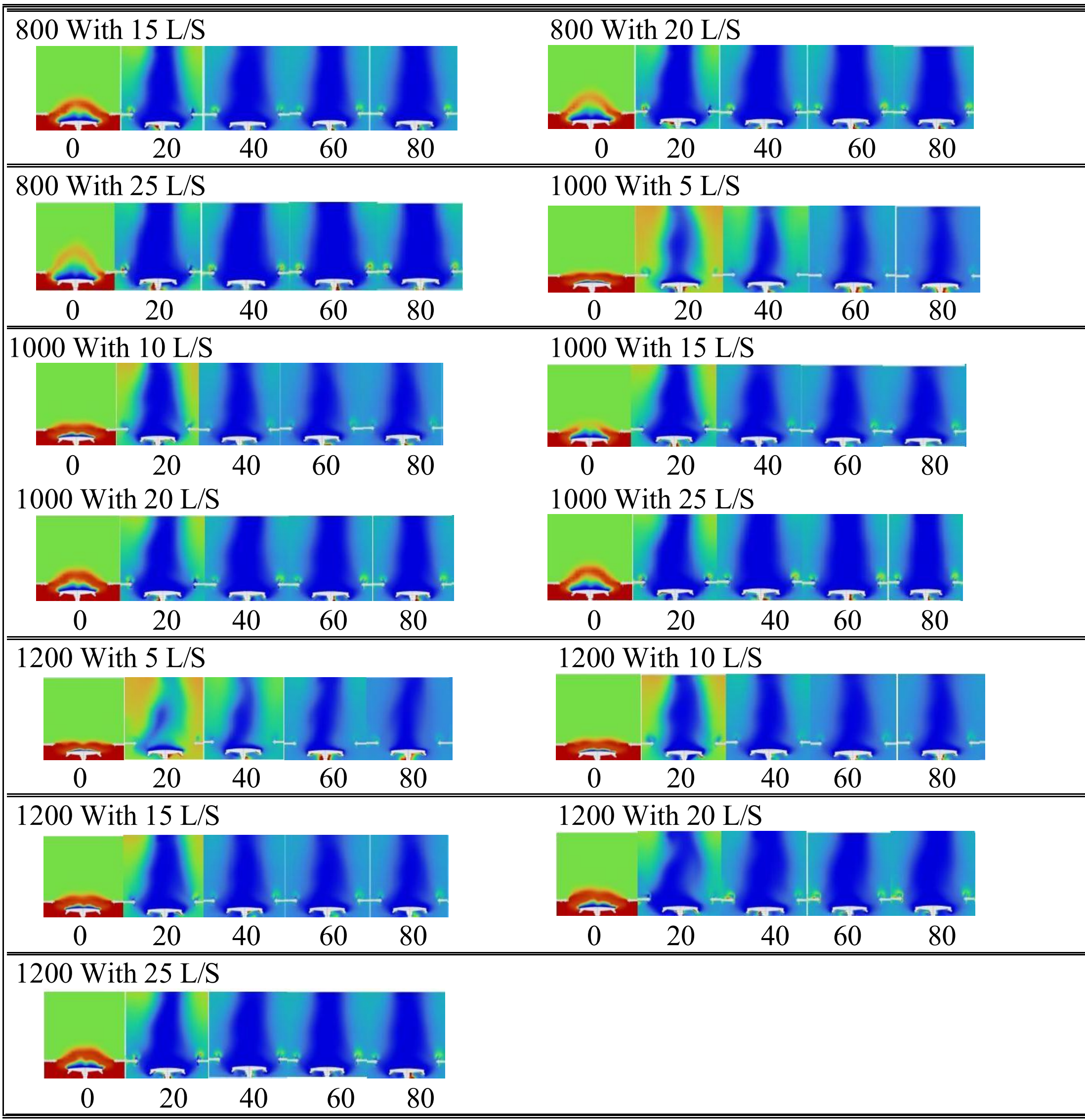


Figure 4. Density Distribution Contours

3.3 Visualization Density Distribution

From the results **Fig.5** above using density, it was found that with increasing variables, the results did not differ significantly from each increase in oxygen flow rate and impeller speed. In the research results (Namira et al., 2021), it was found that the longer the stirring time and the increase in stirring speed, the lower the density value. From their results, the lowest density value was obtained in sample 8 with a homogenization time of 4 minutes and a speed of 22,000 rpm, amounting to 0.76 g/mL, while the highest density value was obtained in sample 1 with a homogenization time of 2 minutes and a speed of 18,000 rpm, amounting to 0.88 g/mL. The results we obtained from the literature can be said to be inversely proportional to literature because the density results, we obtained were constant and did not vary much with variations in speed and oxygen flow rate. However, a standard deviation must also be performed for more precise results because only 3 points were taken [14].

Based on other literature, the density value of the mixture did not show a consistent trend over the mixing time. This is different from the literature that used alginate solution, where the density increased over time due to the increased dissolution of the solute. The mixing system used in this final project is a three-phase mixture (water, $CaCO_3$ solid, and O_2 gas), where homogenization is not determined by the dissolution of solutes, but rather by the even distribution of solid particles in the solvent. Therefore, a more appropriate homogenization indicator is the standard deviation of density between sampling points. The results show that the standard deviation decreased significantly after stirring time >120 minutes, reaching a value <0.01 at 140 to 180 minutes. This value indicates that the mixture was homogeneous, even though the average density showed fluctuations. Based on literature in the field of chemical/pharmaceutical engineering, a standard deviation value ≤ 0.01 g/mL is generally considered the homogeneity threshold for suspension mixtures, and we used this as the standard deviation calculation benchmark (0.01) [15].

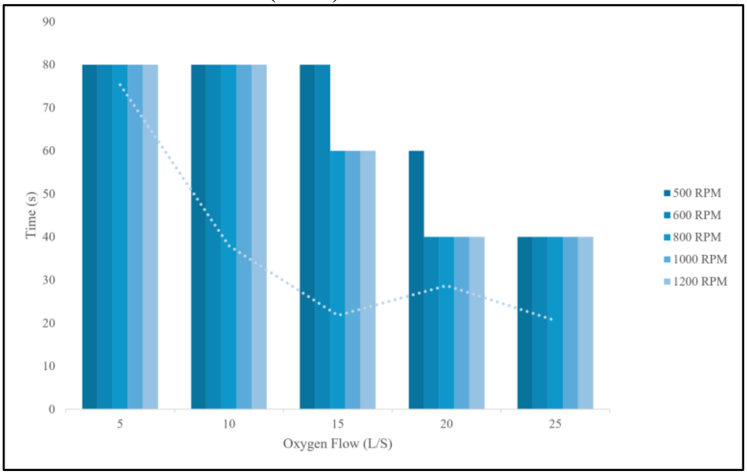


Figure 5. Visualization Density Distribution

To quantitatively evaluate the mixing quality, the standard deviation of density among the three sampling points was analyzed. A lower standard deviation indicates a more uniform density distribution and, consequently, a higher degree of spatial homogeneity. Although temporary fluctuations in the standard deviation were observed during the early mixing stage due to particle recirculation and local concentration differences, the overall trend showed a continuous decrease as mixing progressed. Under the condition of 1200 RPM and an oxygen flow rate of 25 L/s, the standard deviation decreased to below 0.01 after 60 s, indicating that the suspension had reached a homogeneous state. These quantitative results are consistent with the density contour visualization and provide additional evidence that increasing impeller speed and oxygen flow rate enhances mixing performance. Nevertheless, further evaluation using dimensionless numbers, such as the Reynolds and Sherwood numbers, may provide a more comprehensive assessment of the mixing process.

4 Conclusions

The CFD results showed that increasing the impeller speed and oxygen flow rate improved the flow circulation and accelerated the mixing process in the side-entry mixer. The flow pattern was dominated by axial and combined axial–radial flow, which promoted a more uniform distribution throughout the vessel. The optimal condition was obtained at 1200 RPM with oxygen flow rates of 20–25 L/s, where complete mixing was achieved within approximately 40 seconds. The Reynolds and Sherwood numbers generally increased with rotational speed and oxygen flow rate, indicating stronger turbulence and improved mass transfer. However, the mass transfer coefficient fluctuated, possibly due to variations in the concentration data.

Further studies should evaluate wider operating ranges, different impeller positions and designs, as well as power consumption and Power Number to determine the balance between mixing performance and energy requirements. Experimental validation is also recommended to improve the reliability of the CFD model.

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