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Investigation of Bubble Breakup in Venturi-Type Microbubble Generator with Twisted Baffle

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Abstract. The microbubble generator is an essential technology in various applications, such as water treatment, due to its ability to improve mass transfer efficiency, particularly ocygenation. Bubble breakup is a critical process that affects bubble size and its distribution in the solution, In this study, the experimental investigation focuses on analyzing the bubble breakup phenomenon in a venturi-type microbubble generator (MBG) equipped with a twisted baffle. Water flow rates (Q_L) and air flow rates (Q_G) were varied at Q_L = 40 and 60 lpm and Q_G = 0,2 and 0,6 lpm. The methods used in this study include visualizing the bubble breakup process using a high-speed camera and measuring pressure fluctuations in the MBG detected by a pressure transducer. The analysis involves Power Spectral Density (PSD), Probability Density Function (PDF) of pressure drop, and Discrete Wavelet Transform (DWT). The tests were conducted with variations in water and air flow rates, as well as pressure measurements to understand the interaction between liquid and gas flows. The analysis results indicate that the presence of the twisted baffle significantly increases flow turbulence, which accelerates the bubble breakup process. This process produce smaller and more evenly distributed bubbles, which is crucial for enchancing dissolved ocygen (DO) levels in the solution.

Keywords Bubble breakup, microbubble, return flow, twisted baffle

1. INTRODUCTION

Microbubbles are gas bubbles with a diameter smaller than 100 µm, that have a larger surface area compared to regular bubbles. These bubbles can increase the amount of oxygen dissolved in water, improve mass transfer, and remain stable in the liquid for longer. Microbubbles are created using a device called a microbubble generator (MBG), which uses flow of water and air to form these small bubbles. The venturi-type microbubble generator is commonly used because of its simple design, high efficiency, reliability, and safety. It can produce fine bubbles on a large scale while consuming low energy. Previous study have examined the bubble breakup mechanism influenced by various factors, but these studies limited to conventional venturi MBG and the adding a swirl. The main challenges lie in improving microbubble generator efficiency and simplifying device geometry for better performance. Therefore, this study explore the influence of a twisted baffle in a venturi MBG on the bubble breakup mechanism.

In this study, a twisted baffle is added to the inlet of a ventury-type MBG to make the water flow more turbulent, which helps break larger bubbles into smaller ones. This effect caused by the baffle allows for more uniform and smaller bubbles. This research

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focuses on observing how bubbles breakup inside the venturi MBG with the addition of the twisted baffle. The experiment will use a high speed camera to record the bubble formation process, the image will be analyzed using MATLAB R3032b software and measurements of pressure fluctuations occurring in the MBG will be detected by a pressure transducer.

2. LITERATURE REVIEW

The bubble breakup mechanism involves a balance between external pressure from the surrounding liquid, which tries to break the bubble apart, and the surface tension of the bubble, which resist this deformation and tries to maintain its shape.

Bubble breakup in a venturi-type swirl microbubble generator has been studied in. They developed this type of generator to better understand the breakup process. Using high-speed cameras, they recorded the movement, deformation, and breakup of bubbles in water flowing at different speeds. Their findings revealed three patterns of bubble breakup, breakup along the direction of movement, rotation of the bubble before splitting into two smaller bubbles and explosive breakup into multiple smaller bubbles. Additionally, statistical analysis showed that bubbles tended to move toward the tube walls, while the smaller bubbles moved toward the center of the flow.

Then used computer simulations to study bubble breakup in venturi-type bubble generators. They applied a techniques called Large Eddy Simulation (LES) to model how bubbles bnehave and break apart inside the venturi. The study found that venturi channels with longer throats and optimal convergence and divergence angles improve friction between the liquid and gas phases, speeding up bubble breakup. They also discovered that varying the flow at the inlet in a random way helps create realistic turbulence, enchancing bubble breakup efficiency. Next focused on how bubbles merge and break apart. Using high-speed imaging, they analyzed how bubbles deform and break under high and low turbulence conditions. The study found thath turbulence fluctuations, shear forces, and the stability of the bubble’s surface all impact the presence of surfactants significantly influence bubble behavior.

The transport and breakup of bubbles in two small rectangular venturi channels with throat sizes of 1mm x 1mm and 2 mm x 2 mm were visually by. Using high-speed cameras, they observed that the smaller venturi produced finer bubbles and had more efficient breakup characteristics. As bubbles entered the diverging section of the venturi, they deformed significantly due to jet flows, breaking into two fragments and then further splitting in the recirculation zone. At higher flow rates, intense surface instability caused the bubbles to collapse entirely. The study confirmed that smaller venturi channels are more effective for producing fine bubbles.

The effect of the number of baffles on the performance of a venturi microbubble generator was explored by. The study used a venturi-type microbubble generator with different numbers of baffles. Baffles were added to control the flow of microbubbles and break larger bubbles into smaller ones. The results showed that adding baffles improved the efficiency of microbubble generation and resulted in better bubble size distribution, with most bubbles having a diameter of around 73 µm.

The findings from the studies provide valuable insights into bubble breakup mechanism an their influencing factors, particularly in venturi-type microbubble generators. It was observed that the breakup process results from the balance between external liquid pressure and the surface tension of bubbles, with three different patterns.Venturi channel design significantly impact bubble breakup efficiency. Longer throats and optimized convergence-divergence angles enchance friction between liquid and gas phases, accelerating the breakup process. Randomized inlet flow durther promotes realistic trubulence, improving the overall efficiency of bubble generation. Similarly, turbulence intensity, shear forces, and the surfactant presence were found to influence the stability and behavior of bubbles during the breakup process. The addition of baffle was another critical factor in improving microbubble generation. These findings have important implications for optimizing microbubble generator designs.

3. METHODS

The experimental apparatus in the Fig. 1 consisted of a venturi-type microbubble generator with a twisted baffle at the inlet. The setup included various components such as pump, valves, flowmeters for both water and air, a microbubble generator with twisted baffle in the Fig 2, a differential pressure transducer for measuring pressure fluctuations, and a high speed camera Phantom Veo 610s, has maximum resolution of 1280 x 960 and with Navitar Telecentric Lens 2.0 1-8114. All observations were made at a frame rate of 5600 fps.

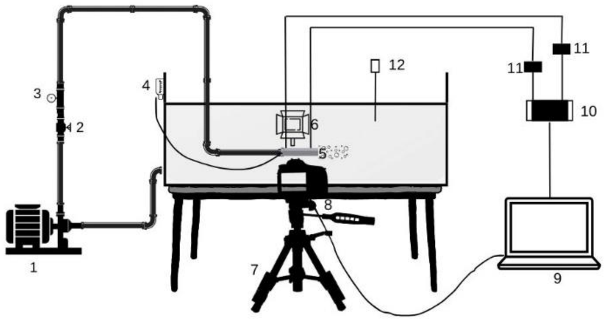


Figure 1. Research apparatus scheme

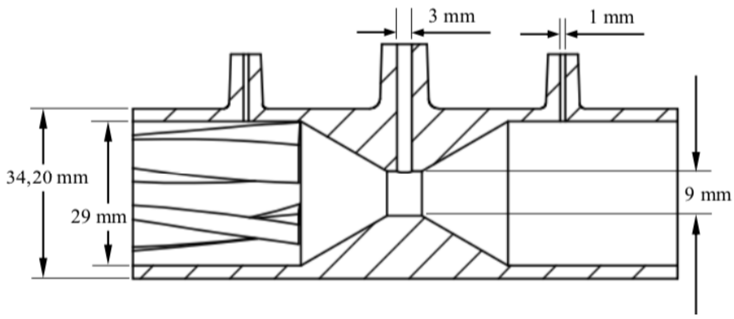


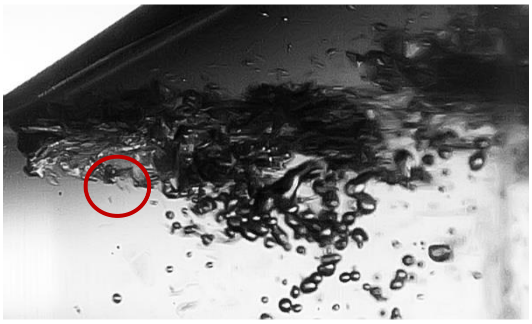
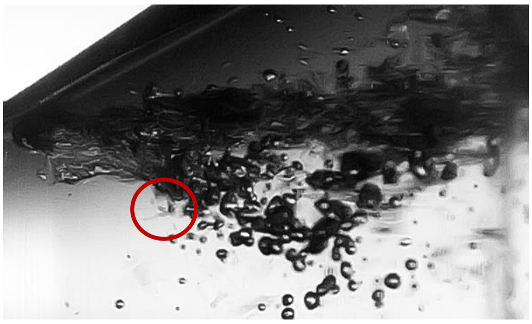
Figure 2. Microbubble generator with twisted baffle

The study involved varying the water flow rate and air flow rate to observe their effects on bubble breakup. The specific flow rates tested were 40 and 60 lpm for water, and 0.2 and 0.6 lpm for air. High speed imaging was utilized to visualize the bubble breakup process. Additionally, pressure fluctuations were analyzed using Power Spectral Density (PSD) and Probability Density Function (PDF) of pressure drop, Discrete Wavelet Transform (DWT) was also employed for further analysis of the data. The methodology aims to provide insights into how the twisted baffle design influences bubble dynamics and the efficiency of the microbubble generator, contributing to the overall understanding of mass transfer processes in such systems.

4. RESULTS

A significant focus of the study is on the phenomenon of bubble breakup. The results indicate that the introduction of the twisted baffle at the inlet of the microbubble generator plays a crucial role in enchancing turbulence and mixing. This increased turbulence facilitates the breakup of larger bubbles into smaller ones, which is essential for improving mas transfer efficiency.


a. t = 2.561 s   b. t = 2.562 s

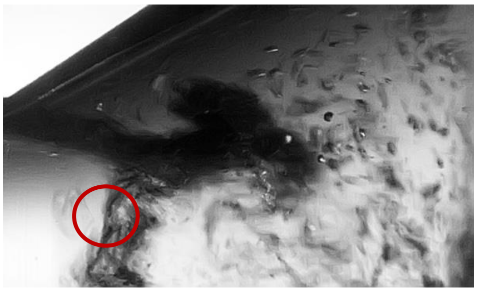
c. t = 2.564 s   d. t = 2.565 s

Figure 3. Bubble breakup at Q_L= 40 lpm, Q_G = 0,2 lpm

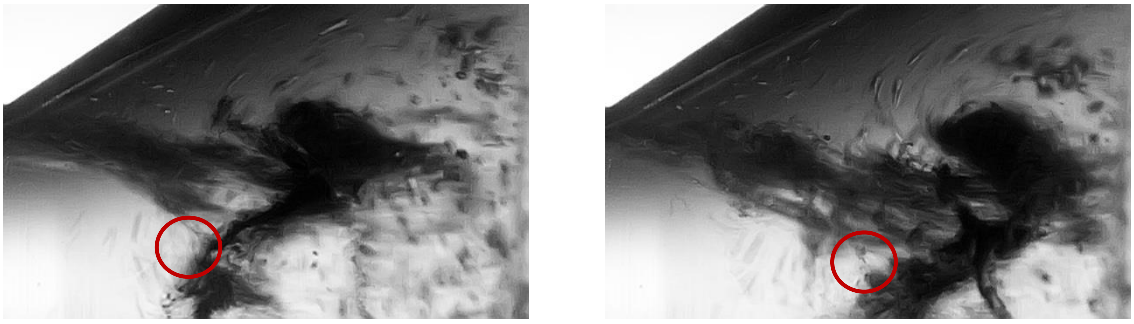

a. t = 0.175 s   b. t = 0.176 s


c. t = 0.177 s   d. t = 0.178 s

Figure 4. Bubble breakup at Q_L= 40 lpm, Q_G = 0,6 lpm

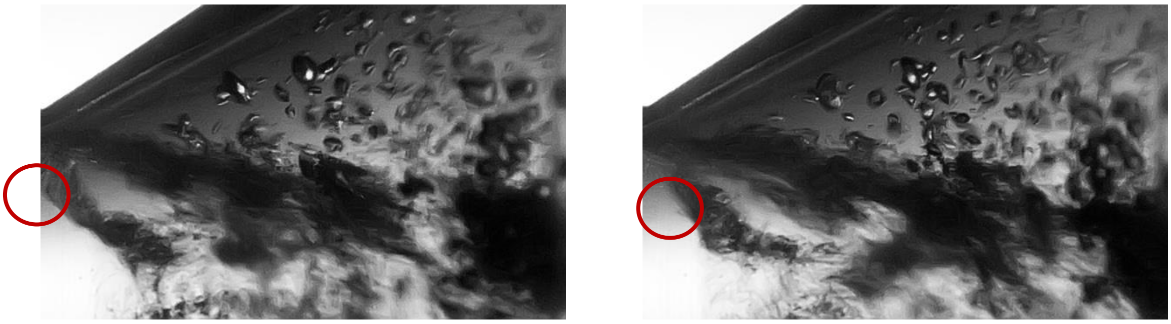



a. t = 7.060 s   b. t = 7.061 s

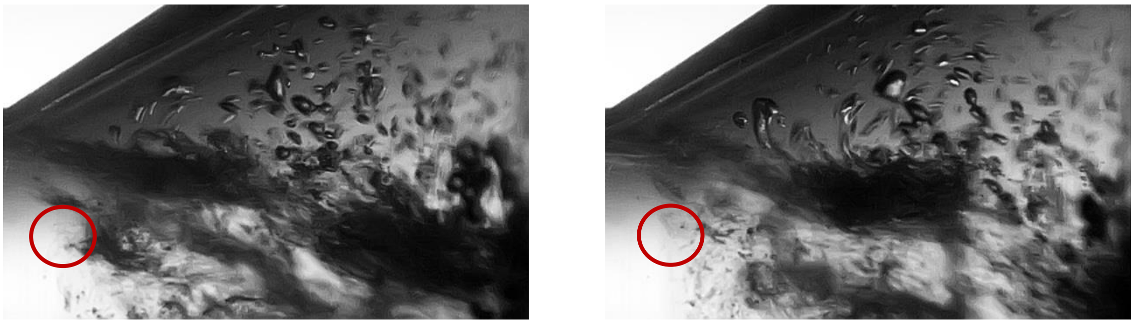


c. t = 7.062 s d. t = 7.062 s

Figure 5. Bubble breakup at Q_L= 60 lpm, Q_G = 0,2 lpm



a. t = 0.082 s b. t = 0.083 s



c. t = 0.083 s d. t = 0.084 s

Figure 6. Bubble breakup at Q_L= 60 lpm, Q_G = 0,6 lpm

Figure 3 until Figure 6 are bubble breakup visualization. High speed camera images showing the process of bubble formation and breakup under different flow conditions. The analysis reveals that at higher water flow rates, the frequency of bubble breakup increases, leading to a more uniform distribution of smaller bubbles. This is particularly important for applications were effective gas-liquid interaction is required, such as in wastewater treatment processes.

Differential pressure measurements were conducted to assess the pressure drop accros the microbubble generator. The findings indicate a clear correlation between the flow rates and the pressure changes observed.

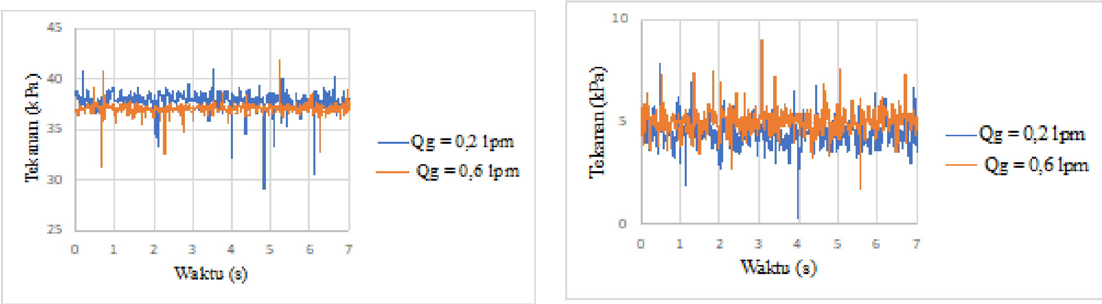


Figure 7. Pressure Signal at MBG at Q_L = 40 lpm

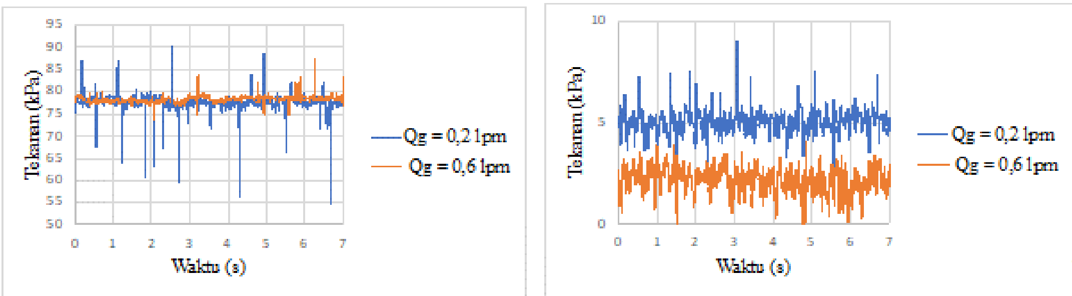
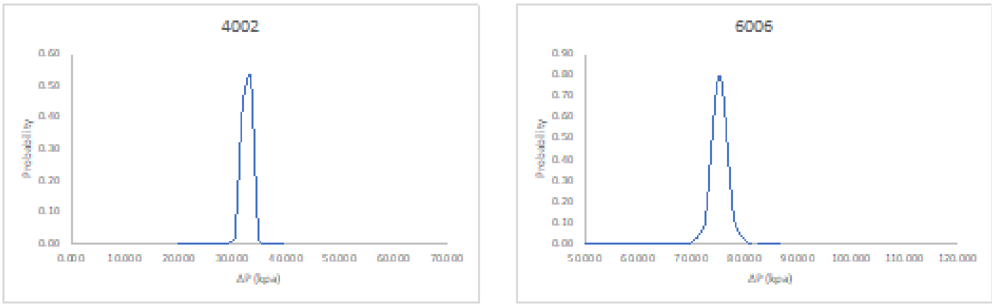


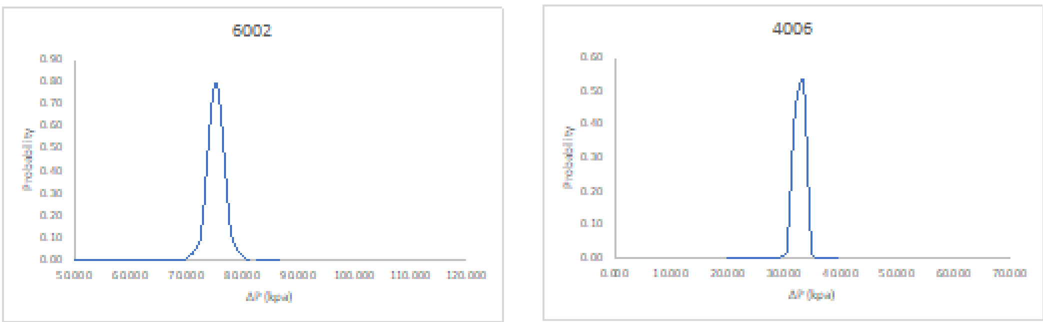
Figure 8. Pressure Signal at MBG at Q_L = 40 lpm

The pressure signals observed at the microbubble generator (MBG) provide valuable insights into the inlet and outlet conditions. At the inlet (left), the pressure exhibits higher and more noticeable fluctuations compared to the outlet. For lower gas flow rates (Q_G= 0,2 lpm), the inlet pressure remains relatively stable around a higher baseline with minor variations. However, at the higher gas flow rates (Q_G= 0,6 lpm), the pressure values decrease and show sudden drops, indicating potential instabilities or turbulence in the flow. On the other hand, the outlet (right) shows significantly lower and less fluctuating pressure values. As the gas flow rate increase, the outlet pressure baseline drops further and becomes more irregular at Q_G= 0,6 lpm. Overall, the results indicate a significant pressure drop across the MBG, which correlates with the increase in gas flow rates. The higher fluctuations at the inlet may be attributed to flow resistance, turbulence, or gas-liquid interaction, while the systems, where flow expansion in the divergent section leads to a decrease in pressure.



Q_G= 0,2 lpm Q_G= 0,6 lpm

Figure 9. PDF pressure drop at Q_L = 40

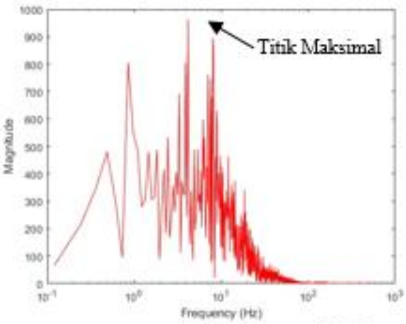


Q_G= 0,2 lpm Q_G= 0,6 lpm

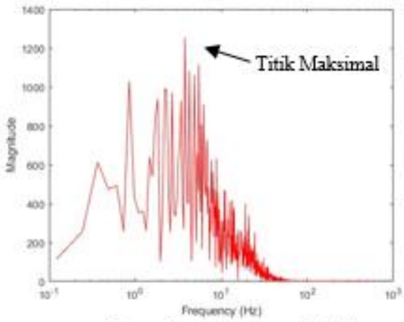
Figure 10. PDF pressure drop at Q_L= 40

An increase in water flow rate (Q_L) has a more noticeable effect on pressure drop compared to the gas flow rate (Q_G). Higher liquid flow leads to more energy loss due to friction and interaction between the water and gas. The turbulence created by the baffle, combined with a higher water flow rate, causes greater pressure variations. Increased turbulence results in more uneven flow, which expands the pressure distribution and creates a flatter peak in the PDF graph. A flatter PDF peak indicates that the baffle effectively controls pressure fluctuations, stabilizes the system, and allows it to operate under different flow rates. Adding a baffle also narrows the water flow area, increasing its speed and causing a higher pressure drop.

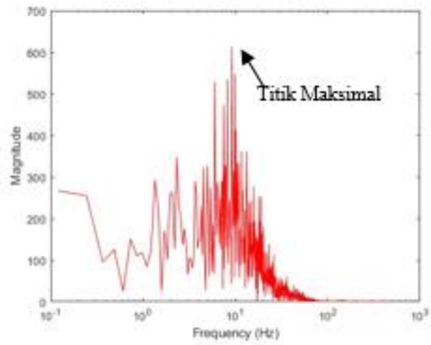
Power Spectral Density (PSD) is a signal processing method used to represent pressure fluctuations in the frequency domain through Fast Fourier Transform (FFT). The PSD graph shows the distribution of energy or intensity of pressure fluctuation across different frequencies.



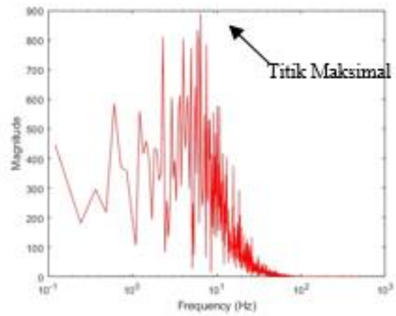
a. Inlet $Q_G = 0{,}2$ lpm



b. Outlet $Q_G = 0{,}2$ lpm

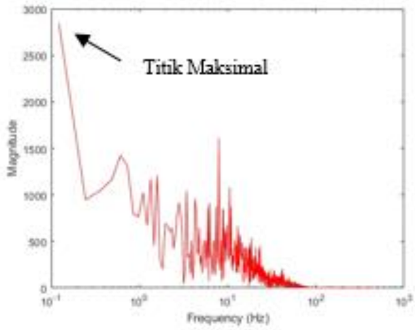


c. Inlet $Q_G = 0{,}6$ lpm

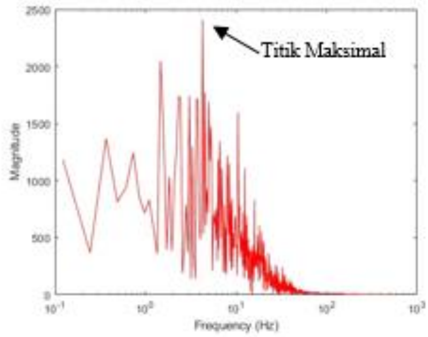


d. Inlet $Q_G = 0{,}6$ lpm

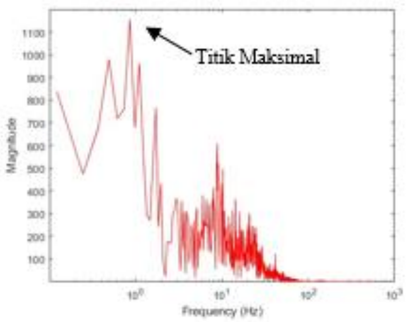
Figure 11. PSD at $Q_L =$ 40 lpm



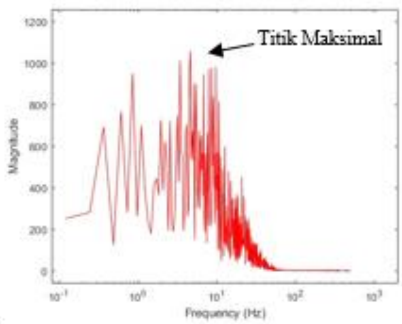
a. Inlet $Q_G = 0{,}2$ lpm



b. Outlet $Q_G = 0{,}2$ lpm



c. Inlet $Q_G = 0{,}6$ lpm



d. Inlet $Q_G = 0{,}6$ lpm

Figure 12. PSD at $Q_L =$ 60 lpm

The magnitude represents the amount of energy contained in a signal at specific frequencies. At low liquid flow rates (Q_L), pressure fluctuation are more dominant at lower frequencies. As Q_L increase, the overall intensity of pressure fluctuation also rises, leading to an upward curve in the PSD graph and higher magnitude values. Similarly, increasing the gas flow rate (Q_G) amplifies pressure fluctuation due to turbulent interactions between gas and liquid. Baffles are particulary effective in stabilizing pressure, especially at the outlet.

The study also uses Discreate Wavelet Transform (DWT) to break down the original signal into approximation and detail components, decomposing it up to 8 levels with the Daubechies 4 model. MATLAB R2023b software with wavelet toolbox was used for the analysis.=

Table 1. Signal decomposition at Q_L= 40 lpm and Q_G = 0,2 lpm

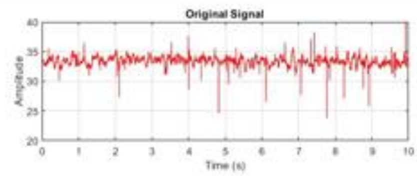
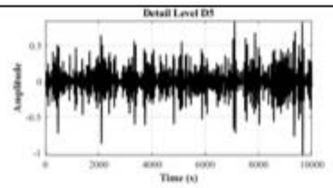
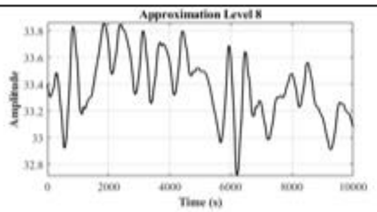
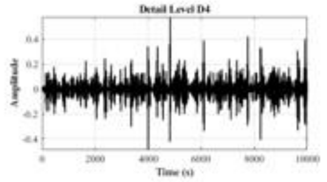
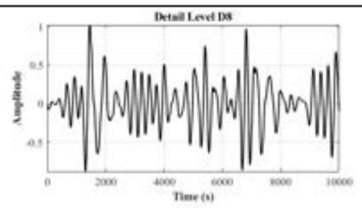
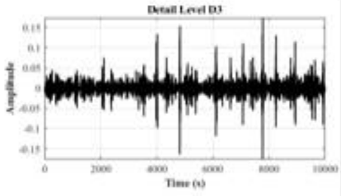
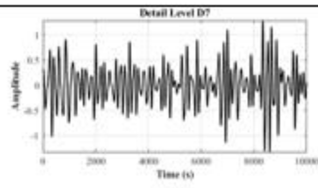
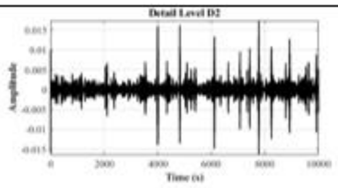
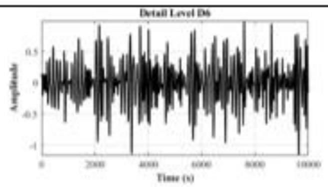
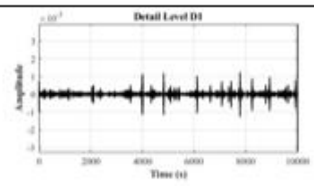
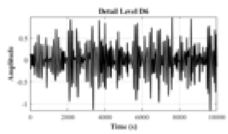
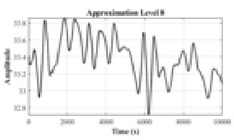
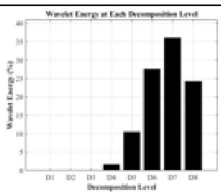
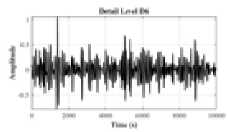
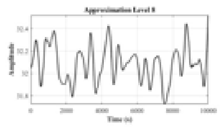
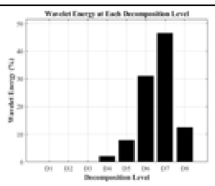
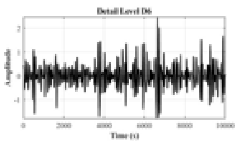
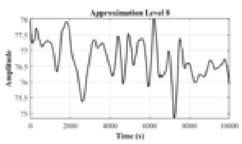
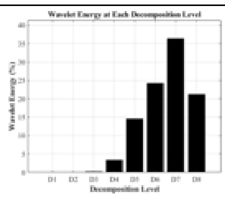
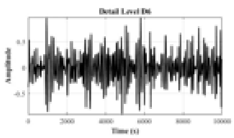
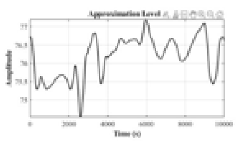
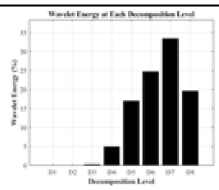
S		D5	
A8		D4	
D8		D3	
D7		D2	
D6		D1	

Table 1 illustrates the detailed results of signal decomposition from pressure data in this study. Component D1 represent the smallest scale with the highest frequency, while D2 to D8 depict progressively lower frequency bands. Conversely, Ab reflects the signal's approximation at a large scale with low frequencies.

Table 2. analyzes the wavelet decomposition of a venturi MBG with a twisted baffle based on variations in (Q_L) and gas flow rate (Q_G). Component D6 highlights the high frequency elements of the flow data for each variation. Higher amplitude fluctuations in D6 indicate more intense turbulence in the flow. Meanwhile, A8 represents low-frequency components that show the primary flow trend, where smoother amplitudes suggest greater flow stability. The wavelet energy graphs reveal energy distribution across wavelet decomposition levels. Higher energy at specific levels refrects the flow's intensity and the dominance of particular frequencies.

Table 2 Wavelet analysis of microbubble generator venturi with twisted baffle

Q_L (lpm)	Q_G (lpm)	D6 (a)	A8 (b)	Wavelet Energy (c)
40	0,2			
	0,6			
60	0,2			
	0,6			

The findings suggest that fluctuation in D6, corresponding to higher turbulence levels, enchance the bubble rupture process. Turbulence increases the shear force and pressure gradient, which facilitates the fragmentations of larger bubble into smaller ones. Meanwhile, the smoother amplitude of A8, indicating flow stability, contributes to consistent bubble formation and size distribution. The energy levels at different decomposition scales also provide insight into how turbulence and flow characteristics at specific frequencies affect bubble rupture dynamics.

5. DISCUSSION

This study investigated how bubbles breakup in Venturi microbubble generator with a twisted baffle, focusing on how design and flow rates of water and air affect bubble increase turbulence, helping to break larger bubble into smaller ones, which improves oxygen transfer in application like water treatment. Higher water and air flow rates led to more bubble fragmentation, confirming the role of turbulence in enhancing system performance. While the findings align with previous research, this study highlights the specific impact of twisted baffles. Some unexpected variations in bubble size suggest further research is needed to fully understand the forces at play.

6. CONCLUSION

Bubble breakup in a venturi microbubble generator (MBG) with twisted baffles is greatly influenced by its design and operational condition. The twisted baffles and the optimized geometry of the venturi play a critical role in bubble breakup effectively. This process is driven by pressure difference between the throat and divergent sections of the venturi, where high fluid velocity and low pressure create shear forces strong enough to split bubbles. Additionally, turbulence in the system significantly contributes to bubles breakup, as shown by power spectral density (PSD) analysis. Higher turbulence leads to smaller and more evenly distributed bubbles.

The study also highlight that pressure variations depend on water and gas flow rates, as revealed through probability density function (PDF) analysis. When gas flow rates increase, pressure at the throat rises, accelerating bubble breakup, while lower gas flow rates result in shower buble dispersion. Using discrete wavelet transform (DWT), researchers were able to track changes in bubble behavior over time and space, providing deeper insights into the dynamics of the breakup procces.

The improved efficiency of bubble breakup has practical benefits, including increase dissolved oxygen levels in the liquid, which enhances oxygen transfer efficiency – a crucial factor for application such as wastewater treatment and aeration. These findings underscore the importance of carefully designed ventury MBG system and tailored flow conditions to optimize performance and achieve consistent, efficient bubble generation.

7. LIMITATION

This study provides valuable insights into bubble breakup in a venturi microbubble generator with twisted baffles, but it has some limitations. The experiments were conducted using specific water and air flow rates, so the results may not fully apply to other flow condition. The high-speed camera imaging used in the studyhad challenges in capturing the complex behavior of bubbles in turbulent flows. Additionally, the analysis methods, such as PSD and DWT, come with certain assumptions and limitations that could affect how the results are interpreted. Finally, the experiments were performed in a controlled laboratory setting, which doesn't entirely reflect real-world conditions, such as temperature variations or the presence of impurities. Therefore, further research is needed to confirm these findings under more diverse and realistic conditions.

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