Journal of Advanced Technology and Multidiscipline Vol. 04, No. 01, 2025, pp. 8-12

Original article

Analyzing the Formation of Nanobubbles and its Effect on the Stability of Dissolved Oxygen in Water

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Received 10 April 2025; Accepted 12 May 2025
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***Abstract*— Nanobubbles (NB) have attracted considerable attention from researchers due to their unique characteristics, one of which is their ability to increase the amount of dissolved oxygen (DO) in liquids, making them a promising technology for various applications, such as water treatment and aquaculture. This study investigates the generation of NBs using a custom-designed cartridge nozzle and evaluates their effectiveness in maintaining elevated DO concentrations. Experiments were conducted under a controlled gas pressure of 400 N/m², comprising a 30-minute active phase with the generator turned on, followed by a 30-minute passive phase with the generator off, to assess NB formation and stability. Particle size analysis revealed the production of uniformly distributed NBs averaging approximately 600 nm, which remained structurally stable even after gas input ceased. During the active phase, DO levels increased sharply, peaking at 28.51 mg/L by the 10th minute. Although a gradual decline was observed after pressurization stopped, DO levels remained significantly higher than the baseline, indicating the prolonged oxygen retention capability of NBs. This performance is attributed to the unique properties of nanobubbles (<1 μm) that exhibit higher stability, slow dissolution kinetics, high zeta potential, and favorable interfacial interactions compared to conventional bubbles (>1 mm). Overall, the cartridge nozzle-based method demonstrates strong potential for applications in water treatment, aquaculture, and other processes requiring efficient and sustained oxygen delivery.**

***Keywords*— Nanobubbles, Dissolved Oxygen, Bubble Stability, Cartridge Nozzle.**

I. INTRODUCTION

Nanotechnology has attracted much attention from researchers in recent years. Among the many emerging nanotechnologies, nanobubble technology has received much attention due to its usefulness in various applications, such as water treatment [1], [2], medicine [3], [4], and aquaculture [5][6]. Nanobubbles exhibit several remarkable characteristics in aqueous solutions, including higher solubility, high zeta potential, free radical generation, exceptional stability against coalescence, large surface area, and high energy release through bubble disintegration [7].

Nanobubbles (NBs) are nanometer-sized gas bubbles in a liquid, with a diameter not exceeding 1 μm [5], [8], [9]. This is in contrast to regular microbubbles (less than 50 μm in diameter) or larger conventional bubbles (more than 1 mm in diameter) [10]. NBs have high stability and can be suspended in liquids for a long time, compared to larger gas bubbles [11]. The stability of NBs is due to the surface charge that prevents them from coalescing with other bubbles. The high pressure in NBs is due to their small size, which affects their physical and chemical interactions with the surrounding environment [12]. The smaller the bubble size, the higher the oxygen pressure value in water, indicating that NBs increase the oxygen value in water to a higher level compared to microbubbles (10-50 mm diameter) [11], [13], [14].

Several previous studies have used pressure cartridge nozzles to create friction and turbulent flow within the liquid. These conditions help the formation of very small air bubbles, known as nanobubbles, and have stable properties [15], [16]. This preliminary study focuses on the generation of NBs using a homemade nanobubble generator, aiming to investigate the correlation between NB size and the enhancement of dissolved oxygen (DO) levels. By analyzing the formation mechanism and stability of the generated NBs, this work aspires to contribute foundational insights toward the optimization of aeration technologies for applications in environmental engineering, agriculture, aquaculture, medical therapy, and other oxygen-dependent processes. A summary of our study is depicted in Figure 1.

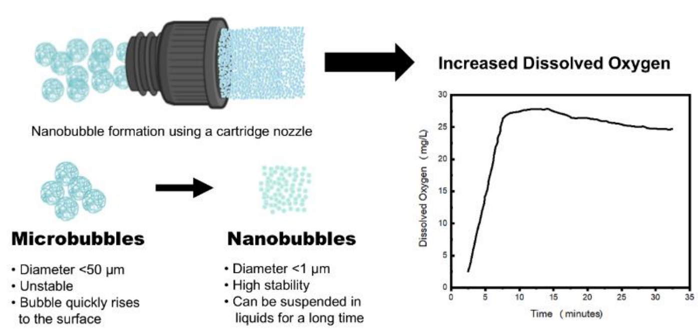

Figure 1. The ability of nanobubble to increase DO.

AS Ansari, et al. (2025), Analyzing the Formation of Nanobubbles and its Effect on the Stability of Dissolved Oxygen in Water, Available at https://e-journal.unair.ac.id/JATM/issue/view/2930
DOI: 10.20473/jatm.v4i1.71660

II. Experimental Method

The homemade nanobubble generator was employed to produce NBs in water, using similar principles to our previous studies [17], [18]. The experiment was carried out under an input gas pressure of 400 N/m² over a total duration of 60 minutes. During the initial 30 minutes, the generator was actively operated to facilitate NB formation. Subsequently, the system was turned off for the remaining 30 minutes to observe the stability and evolution of NB size over time in the absence of active generation. The size distribution of the generated nanobubbles was measured using a Malvern Zetasizer Pro (ZSU 3200) particle size analyzer. Meanwhile, the DO concentration in water was monitored using a YSI Professional Series DO meter. The initial DO concentration in the water prior to nanobubble generation was recorded as 2.42 mg/L. The collected data were analyzed to evaluate the relationship between NB and the enhancement of DO concentration, as well as to assess the stability of the NBs over time. The procedure was repeated several times (more than 10 times) for reliability and accuracy in measurement. The error in DO measurement and average bubble size was calculated to be ± 0.5 mg//L and ± 20 nm.

III. Result and Discussion

This research was conducted to evaluate the effect of oxygen gas pressure on the size of NBs formed and the effectiveness of the homemade cartridge nozzle in maintaining their stability after the engine is turned off. The data obtained were analyzed to determine the optimal conditions for forming smaller and more stable NBs, contributing to an increase in the DO level in the water.

NB formation in this setup is governed by a mechanical shearing and chopping mechanism, wherein oxygen gas introduced into the water is subjected to high-speed flow through a custom-designed cartridge nozzle. This dynamic induces the breakup of larger gas bubbles into nanometer-sized bubbles, a process driven by fluid turbulence and shear forces. This hydrodynamic fragmentation, coupled with pressure-induced cavitation effects, is central to nanobubble formation. The schematic illustration of this mechanism is presented in. Figure 2, where the pressure differential and nozzle geometry are crucial for the efficient disintegration of macro- and microbubbles into NBs.

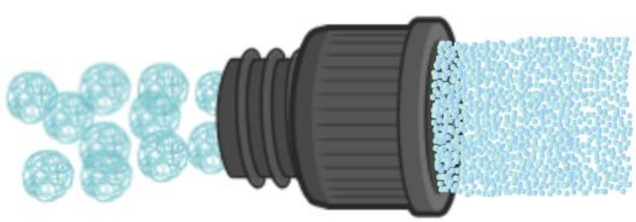

Figure 2. Nanobubble formation using a cartridge nozzle.

The application of external pressure during the gas injection process has proven to be very influential on the nature of the nanobubbles (NB) that form. In the research of Xiaonan Shi (2021), gas was injected through a hydrophobic ceramic membrane at a pressure of 60-80 psi (about 4.1-5.5 atm), and the results showed that the higher the pressure, the smaller the NB size—from about 400 nm to 200 nm [19]. In addition, the model in the study predicts that the pressure inside the NB can reach 120-240 psi (about 8.3-16.6 atm). This shows that higher injection pressure not only helps shrink the size of the NB but also increases the pressure inside, which directly contributes to the stability and mass transfer efficiency in advanced applications. The theoretical calculation of flow velocity and discharge rate was guided by Bernoulli's principle and pressure-flow relationships, which directly influence the resulting bubble size and uniformity [13]. These theoretical foundations are key to optimizing flow velocity and discharge rate, which in turn dictate bubble size distribution and overall NB uniformity.

To monitor the bubble size, a Malvern Zetasizer Pro (ZSU 3200) was used at multiple time intervals during both operational and non-operational phases. Figure 3 depicts the size distribution of generated NBs when the NB generator has the gas pressure on and off. The particle size analysis (PSA) revealed that the average NB size generated under 400 N/m² gas pressure was approximately 600 nm, with a relatively narrow size distribution at off time. The stability of the bubbles was evident from the minimal change in average size during the off-cycle, suggesting that the generated nanobubbles maintained their structural integrity even without continuous pressurization. This stability underscores the effectiveness of the cartridge nozzle in producing persistent, well-dispersed nanobubbles. Interestingly, a slight reduction in average NB size was observed during the non-operational phase. This behavior is likely due to the collapse or dissolution of marginally larger and less stable bubbles, resulting in a population dominated by smaller, more stable NBs. This phenomenon, while expected, highlights a crucial aspect of NB dynamics: nanobubbles tend to self-purify over time as less stable bubbles dissipate while more robust ones persist. Furthermore, bubbles are quite small, and the external pressure is trying to diminish their stability, which can reduce the size of bubbles when the NB generator is off, which is quite an obvious and trivial phenomenon. This outcome aligns with prior theoretical and experimental studies that challenge classical predictions of rapid bubble collapse. The generated NBs can maintain their bubble size, both during the time the gas pressure is turned on (0 to 30 min) and off (30 to 60 min), as evidenced by PSA measurement at different intervals of time (not shown).

Various theories explain the stability of nanobubbles, as they last much longer than predicted by classical thermodynamic theory [20]. Impurity Shielding Theory posits that a monolayer of surface-active substances or contaminants accumulates at the gas-liquid interface, effectively reducing surface tension and inhibiting gas diffusion. This interface acts as a stabilizing "skin," thereby extending the life of the nanobubbles [21]. The Contact Line Pinning describes the mechanical anchoring of nanobubbles at the three-phase (solid-liquid-gas) contact line. This pinning prevents shrinkage by inhibiting the receding motion of the contact line, which is a critical step in bubble collapse, thus preventing the bubble from shrinking quickly and maintaining its shape for longer [22], [23]. Internal Pressure Theory suggests that, contrary to Young–Laplace predictions,

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which estimate high internal pressures in small-radius bubbles, actual experimental measurements show that the internal pressure of nanobubbles is often closer to ambient conditions. This reduced pressure differential results in slower gas dissolution and enhanced long-term stability [20], [24].

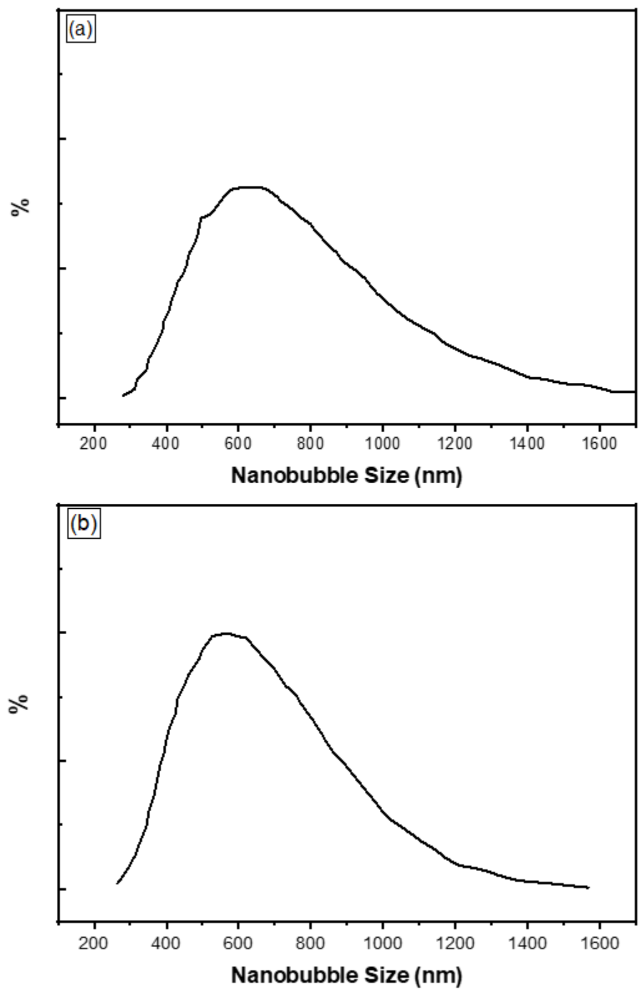

Figure 3. NB size when pressure was (a) on and (b) off.

In parallel, DO measurements were taken to evaluate the effectiveness of NBs in enhancing oxygen availability in water. Figure 4 illustrates the variation in DO levels over time, where the system was pressurized with oxygen gas from 0 to 30 minutes, followed by a non-pressurized phase from 30 to 60 minutes. The initial measurement of DO value in untreated water was 2.42 mg/L.

Upon initiating NB generation with oxygen gas injection, the DO concentration rose rapidly, peaking at 28.51 mg/L within the first 10 minutes of operation. This sharp increase highlights the superior gas transfer efficiency of nanobubbles, driven by their high surface-area-to-volume ratio and the reduced buoyancy that allows them to remain suspended and dissolve gradually. However, an optimal threshold is observed beyond which prolonged operation yields diminishing returns in terms of further DO enhancement. This could be due to the saturation of oxygen in the water. During the bubbling process, the continuous oxygen supply causes the water to become supersaturated. Once bubbling is stopped, the DO concentration tends to decrease back towards equilibrium conditions, as the excess oxygen is gradually released into the air [25].

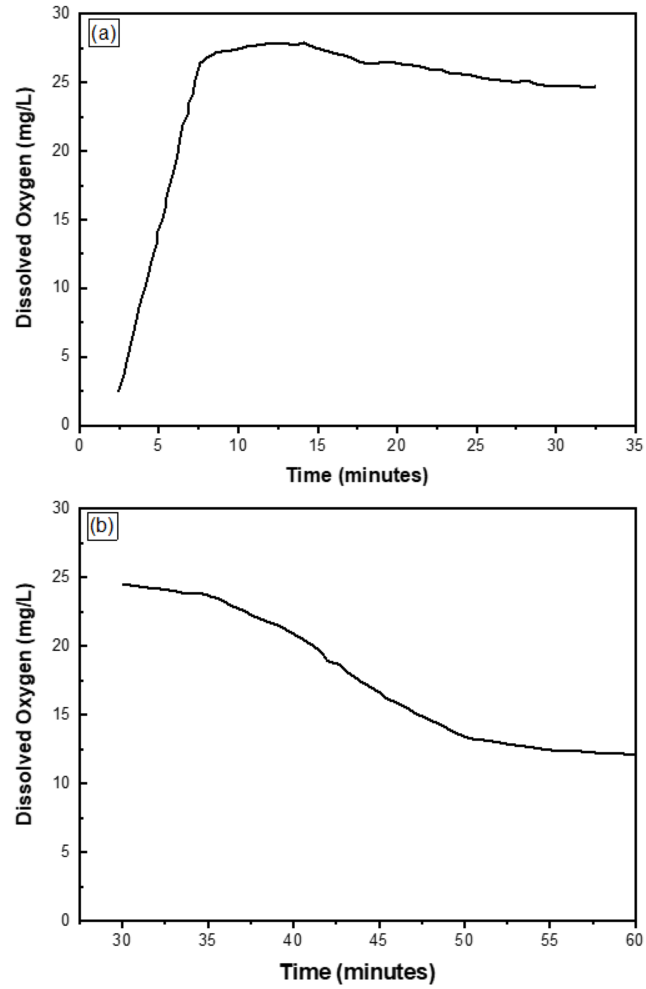

Figure 4. DO values when pressure was (a) on and (b) off.

When the system was turned off after 30 minutes, a gradual decline in DO was observed. Despite the cessation of gas supply, DO levels remained significantly elevated, stabilizing at 12.18 mg/L after 60 minutes, which is nearly fivefold higher than the initial concentration (2.42 mg/L). In comparison, the use of a microbubble nozzle under similar pond conditions, water volume, and aeration duration (60 minutes) only increased DO levels from 7.4 mg/L to 9.1 mg/L at a pressure of 2 Kgf/cm². These results indicate that the nanobubble system is more effective in increasing dissolved oxygen levels than the conventional microbubble system [26].This demonstrates the lingering effect of nanobubbles on oxygen content and underscores their potential for sustained water oxygenation even in passive systems. This behaviour can be attributed to a combination of physicochemical factors that collectively contribute to the stability and effectiveness of NBs in sustaining DO levels. Firstly, the slow dissolution kinetics of NBs enable them to function as miniature reservoirs of oxygen,

DOI: 10.20473/jatm.v4i1.71660

gradually releasing gas into the surrounding medium over time. Additionally, their high zeta potential prevents bubble coalescence, thereby maintaining a uniform dispersion and extending their stability [27], [28]. Interfacial interactions, including electrostatic repulsion and the reduction of surface tension at the gas-liquid interface, further inhibit bubble collapse. Moreover, the intrinsic properties of water, such as viscosity and ionic composition, also play a crucial role in influencing gas solubility and the persistence of NBs within the system [29].

These results collectively affirm that the homemade cartridge nozzle NB generator is a viable, low-cost alternative for producing stable nanobubbles that are effective in significantly enhancing and sustaining DO in aqueous systems. This has direct implications for applications in aquaculture, hydroponics, wastewater treatment, and medical oxygenation technologies, where reliable and efficient oxygen delivery is critical. Currently, we are in the process of utilizing these bubbles for aquaculture and wastewater treatment. The results will be published subsequently. Future work could explore parametric optimization, such as the influence of nozzle geometry, gas flow rate, and fluid composition, to further enhance NB characteristics. Additionally, incorporating real-time imaging or advanced spectroscopy could provide deeper insight into NB behavior at the molecular level, paving the way for smart, adaptive NB systems.

IV. Conclusion

This study demonstrates that a custom-designed nozzle-based system effectively generates stable nanobubbles (~600 nm) that significantly enhance dissolved oxygen levels, even without continuous gas input. With optimization of pressure and nozzle design, this method has the potential to be employed as an energy-efficient oxygenation process across various applications, including water treatment, the aquaculture industry, and increasing the efficiency of biochemical reactions that require dissolved oxygen. Further research into gas type, temperature, and system integration is recommended to optimize and expand the technology's practical use.

Acknowledgment

This work was supported by the National Research and Innovation Agency (BRIN) and the Indonesia Endowment Fund for Education (LPDP) through the Research and Innovation Program for Advanced Indonesia (RIIM) program (Grant Number B-844/II.7.5/FR.06/5/2023 and B-948/III.10/FR.06/5/2023).

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