

**INFLUENCE OF GAS PRESSURE ON THE GENERATION OF
NANOBUBBLES FOR ENHANCED DISSOLVED OXYGEN
(Pengaruh Tekanan Gas Terhadap Pembentukan Nanogelembung Untuk Peningkatan
Oksigen Terlarut)**

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ABSTRACT

Nanobubble (NB) technology produces highly stable nano-sized bubbles with wide applications in water treatment, agriculture, and aquaculture. This study analyses the influence of gas pressure on NB formation, bubble size distribution, and dissolved oxygen (DO) levels in water, aiming to understand how pressure affects NB characteristics and oxygen dissolution efficiency. NBs were generated using a cartridge nozzle with pressurised oxygen gas at pressure values of 0.1, 0.2, and 0.3 kPa for 30 minutes. The results show that gas pressure is a key parameter for nanobubble size and distribution. At a pressure of 0.1 kPa, the average size was 170 nm, decreasing to 110 nm at 0.2 kPa and 93 nm at 0.3 kPa with a more homogeneous size distribution. As the NB size decreased, the DO concentration increased. The initial DO value of 2.42 mg/L increased rapidly over the first 5 minutes to 32.40 mg/L and then to 35.34 mg/L after 30 minutes for 0,3 kPa pressure. This trend is similar to NBs produced at another pressure. This study confirms that gas pressure variation is an important parameter in controlling NB formation and increasing DO, thereby supporting the development of efficient aeration technology for various applications.

Keywords: dissolved oxygen (DO), gas pressure, nanobubbles, nanobubble size

INTRODUCTION

Nanobubble (NB) technology has attracted researchers' attention due to its diverse applications. In contrast to microbubbles, which are 1–1000 µm in size, NBs are tiny gas bubbles with a diameter ranging from 1 to 1000 nm (Atkinson et al., 2019; Favvas et al., 2021; Yaparadne et al., 2024). NBs are widely used across various fields due to their superior stability compared with microbubbles (Agarwal et al., 2011), and other benefits, such as high zeta potential, free

radical formation, and longer persistence, which collectively enhance process efficiency, yield, and selectivity (John et al., 2025). Several fields have utilized NB technology, including medicine (Awlqadr et al., 2025), agriculture (Mamun & Islam, 2025), aquaculture (Liang et al., 2025), and water treatment (Gupta et al., 2025). In agriculture, NB can improve soil quality by increasing the activity of native microorganisms. This can enhance the ability of soil particles to absorb water, increase

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oxygen availability, and improve soil structure (Arablousabet & Povilaitis, 2024). NBs can significantly increase the oxygen content in water. This promotes better fish growth and health, thereby potentially increasing productivity and harvest yields in aquaculture systems (Hoque et al., 2025). The application of NB technology in aquaculture has demonstrated good results. In Nile tilapia culture systems, NB increased dissolved oxygen (DO) concentrations from 6.5 mg/L to 25 mg/L within 30 minutes, indicating a substantial improvement in oxygen transfer performance and water oxygenation efficiency (Mahasri et al., 2018). In shrimp aquaculture, NB has been reported to improve water quality conditions and production performance. The use of NBs in intensive culture systems resulted in improvements in growth performance, feed conversion ratio (FCR), survival rate, and overall productivity compared with conventional aeration methods (Rahmawati et al., 2021).

Recent studies have highlighted the potential of NB for improving pathogen control and environmental management in intensive shrimp farming operations (Liang et al., 2025). Our previous study using the same NB system demonstrated its capability to significantly enhance the DO concentration of aquaculture water in shrimp ponds. DO levels increased up to approximately 16 mg/L during operation and remained stable at around 8 mg/L even after the NB generator had been switched off for 1 h, indicating the prolonged oxygen retention characteristics of NBs in water. Such oxygen stability is particularly beneficial for aquaculture systems because it may reduce fluctuations in DO concentration and provide a more favorable environment for aquatic organisms

NBs are considered to have unique properties due to their size and are therefore often studied in relation to their size effects. NBs have high internal pressure, allowing them to remain suspended in water (Ulatowski et al., 2019). Their stability is further supported by the slow gas diffusion capability at the bubble interface, which prevents gas from escaping easily and maintains stability. The extremely small size and light weight of NBs give them a negligible upward velocity near zero, allowing them to remain suspended in the liquid (FAN et al., 2010; Meegoda et al., 2018).

NBs are formed through nucleation and bubble growth processes initiated by gas injection or gas diffusion into a saturated liquid system (Xiao et al., 2017). During nucleation, gas molecules aggregate and create extremely small gas cavities within the liquid phase. The subsequent growth of NBs occurs when the surrounding solution reaches a supersaturated condition, allowing dissolved gas molecules to continuously diffuse into the bubbles. Under these conditions, interactions between gas molecules and water molecules become more favorable than interactions among gas molecules themselves, promoting the stability and persistence of the bubbles in the liquid medium (Ferraro et al., 2020). The mechanism of NB growth and stability can be explained using the Epstein–Plesset model, which describes how diffusion-driven bubble dynamics are influenced by several important parameters, including surface tension, temperature, internal bubble pressure, and the concentration of dissolved gas in the solution. Variations in these factors directly affect the rate of gas transfer into the bubble and determine whether the NBs continue to grow

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or gradually dissolve. In addition, the presence of surfactants plays a significant role in enhancing NB stability by reducing surface tension at the gas–liquid interface, thereby preventing bubble coalescence and collapse (Alheshibri et al., 2016).

The size of the NBs formed can vary depending on certain parameter conditions. Factors that influence bubble size include gas pressure, system energy, and the solution's physical properties. Gas pressure plays an important role in the formation and size of NBs. The initial stage of the NB nucleation process is triggered by the dissolution of gas into liquid, creating supersaturation conditions. According to Hampton and Nguyen (2010) (Hampton & Nguyen, 2010), the mechanism of NB formation at this stage is related to Henry's Law, which states that the solubility of a gas in a liquid can increase with external pressure. Consequently, supersaturation conditions are reached by applying high gas pressure, which permits more gas to enter. If the supersaturation is high enough, the bubbles formed can reach a nanoscale.

Previously, we developed a pressurized cartridge nozzle equipped with a coated porous membrane that generates friction and turbulent flow in liquids, thereby facilitating the formation of highly stable NBs (Fitriani et al., 2025). In the formation of NBs using a porous membrane nozzle, it is necessary to select the appropriate gas pressure and flow rate (Meegoda et al., 2018). Higher gas pressure can produce bubbles with smaller diameters (Ahmed et al., 2018). High gas pressure increases the gas flow rate entering the NB (NB) generation system, thereby influencing the formation and release behavior of the bubbles. During the process,

bubbles detach from the nozzle after a certain period, commonly referred to as the detachment or release time. An increase in gas pressure and flow rate contributes to a shorter bubble release time and promotes the formation of smaller NBs. Smaller bubbles are considered more stable and provide a larger surface area for gas transfer within the liquid medium. This study investigates the effect of gas pressure on NB size distribution and DO concentration in water. By analyzing the mechanisms involved in NB formation, the research aims to provide a better understanding of how gas pressure affects NB generation and oxygen dissolution efficiency. The findings are expected to support the optimization of aeration technologies and improve their applications in fields such as water treatment, aquaculture, agriculture, and medicine.

MATERIAL AND METHODS

Oxygen NBs were formed by introducing pressurized oxygen gas (99%) into a container containing 100 L of water at room temperature (25 °C) through a membrane nozzle cartridge connected to a pump. NB formation was carried out using a pressure regulator set at 0.1, 0.2, and 0.3 kPa with a gas flow rate of 0.1 LPM. The operating time was 30 minutes for each pressure variation. The total observation time was 60 minutes, with the pump operating for the first 30 minutes to generate NBs. The pump was then turned off for the next 30 minutes to evaluate the stability of the NBs that had formed. The samples from each pressure were collected for analysis to study the evolution of NB size over time without active formation. The size and distribution of NBs were characterized using a Malvern Zetasizer Pro (ZSU 3200) Particle Size Analyser (PSA). The PSA

measurement principle utilizes light scattering caused by particle movement in liquid to determine the size distribution and average diameter of NBs. PSA was performed immediately after NB generation to minimize temporal variations. In addition, the DO concentration in water was measured in situ using a YSI Professional Series DO meter. The initial DO concentration before NB introduction was 2.42 mg/L. The experiments were conducted in triplicate, and statistical analysis was performed using the Analysis of Variance (ANOVA) ($p \leq 0.05$) method.

RESULTS AND DISCUSSION

This research was conducted to determine the effect of gas pressure on the NB formation. The pressures used in this study are 0.1, 0.2, and 0.3 kPa. Pressure variations are expected to affect the size and distribution

of the NBs formed. In addition, this study examines the relationship between NB formation and changes in DO level in solution, as the NBs play an important role in DO concentration.

The formation of NBs begins with the process of nucleation, in which nuclei or clusters of gas bubbles form from dissolved gas molecules in a liquid once a critical concentration is reached (Wang et al., 2019). Under these conditions, the accumulated gas molecules form nanometer-sized bubble nuclei, which can then develop into bulk NBs. NBs produced using the cartridge nozzle method involve applying oxygen gas pressure and forcing it to pass through a tight porous membrane (Alam et al., 2022; Fitriani et al., 2025).

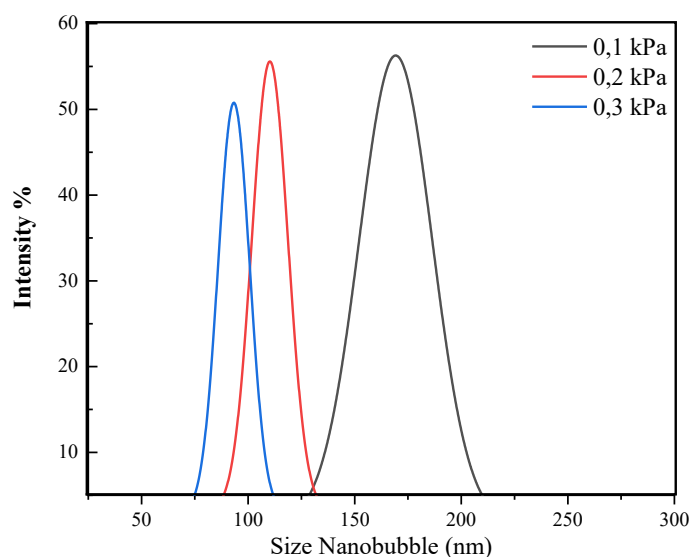


Figure 1. Distribution of nanobubble sizes at gas pressures of 0.1, 0.2, and 0.3 kPa

The size distribution of NBs at different applied pressures is shown in Figure 1, while Table 1 summarizes the main experimental

results, including DO concentration (mean \pm standard deviation), standard error (SE), and average NB size at different gas pressures.

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The size of NBs changes with variations in gas pressure. At a pressure of 0.1 kPa, NBs of an average size of 170 nm were obtained, accompanied by a relatively wide size distribution, indicating polydispersity and the presence of larger bubble fractions. Increasing the pressure to 0.2 kPa resulted in an average size of 110 nm with a narrower size distribution compared to the NBs obtained through a pressure of 0.1 kPa. The average size of NBs decreased further to 93 nm with increasing pressure to 0.3 kPa, accompanied by the narrowest distribution. The calculated FWHM values of NBs size distribution were 40, 20, and 17 nm for the applied 0.1, 0.2, and 0.3 kPa pressure, respectively. The shift of the size distribution peak toward smaller diameters reveals that increasing pressure favors the formation of reduced-size NBs (Bunkin et al., 2021). An increase in gas pressure affects the width of the size distribution of the NBs produced. The higher the gas pressure applied, the narrower the NB size distribution, indicating an increase in uniformity or a decrease in polydispersity. The narrowing of the size distribution at higher gas pressures indicates that the NBs production becomes more homogeneous. The concentration and size distribution of NBs before and after increasing the static pressure have been examined, and it is found that high pressure caused compression and a decrease in the number of large bubbles, which resulted in a narrowing of the NB size distribution (Tuziuti et al., 2017). This indicates that at high pressure, the nucleation environment is more uniform because fluctuations in dissolved gas concentration are reduced. The nearly simultaneous nucleation rate throughout the system produces a relatively uniform bubble population in size.

NB size has been demonstrated to be influenced by gas pressure, with a tendency to decrease as pressure increases (Ahmed et al., 2018; Shi et al., 2021). According to Henry's Law, at a constant temperature, the saturated concentration of gas in a liquid, which represents the amount of dissolved gas and the gas above the liquid surface, has a linear relationship with the partial pressure of the liquid. This relationship is expressed as:

$$C=H\times P_g$$

In equation, C represents the solubility of the gas at a specific temperature in a particular solvent, P_g denotes the partial pressure of the gas, and H signifies the Henry's Law constant. Thus, the higher the gas pressure, the greater the amount of gas that can be dissolved in water (Ferraro et al., 2020). The application of higher gas pressure not only helps reduce the size of NBs but also increases the pressure inside them, which directly contributes to stability and mass transfer efficiency in various applications.

In the NB generation system, the fluid is directed through a narrow gap, such as a nozzle or Venturi. When fluid passes through the narrowing path, the flow velocity increases significantly. The increase in flow velocity causes a decrease in local pressure, which reduces the solubility of gas in water and triggers the formation of NB nuclei. This process is known as cavitation or hydrodynamic cavitation (Li et al., 2021). Theoretical calculations of flow velocity and flow rate are based on Bernoulli's principle and the pressure-flow relationship, which directly affect the size and uniformity of the bubbles produced (Mochamad Anfasa Nurrachman et al., 2023). Under constant experimental conditions, an increase in gas pressure accelerates the rise in DO values in

the solution. An increase in gas pressure improves bubble fragmentation efficiency, producing smaller and more homogeneous nano oxygen bubbles (Yuniar Fauziyah et al., 2023).

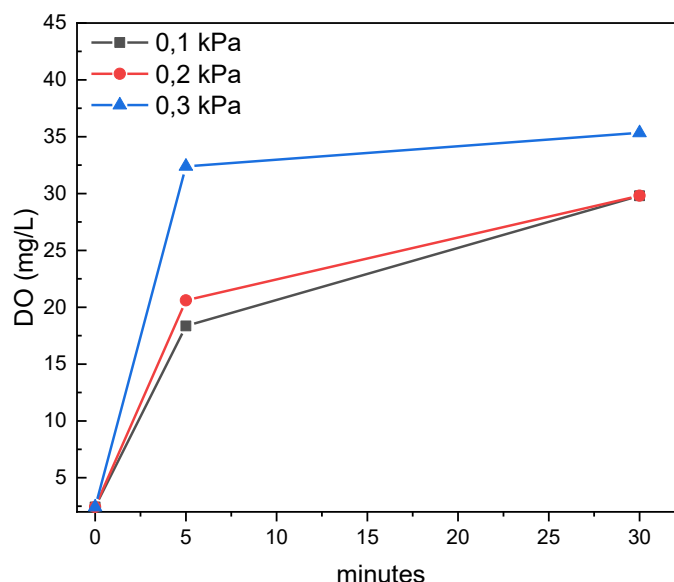


Figure 2. DO values at gas pressures of 0.1, 0.2, and 0.3 kPa with contact times of 5 and 30 minutes

Table 1. Descriptive statistics of dissolved oxygen (DO) concentration

Gas pressure (kPa)	Mean DO	Standard Deviation	SE of Mean	Average particle size (nm)
0.1	24,01	4,29895	1,75	170
0.2	25,30	3,40941	1,39	110
0.3	33,83	1,21159	0,49	93

Figure 2 shows the relationship between time and DO values in the NB formation process at gas pressures of 0.1, 0.2, and 0.3 kPa. An increase in pressure results in higher DO values at each observation time, indicating that pressure significantly affects DO in the solution. The initial DO value before the NB formation process was 2.42 mg/L. At an applied pressure of 0.1 kPa, the DO concentration reached 18.25 mg/L after 5 minutes and was enhanced to 28.80 mg/L

after 30 minutes. Increasing the pressure to 0.2 kPa resulted in DO levels of 20.60 mg/L and 29.81 mg/L at 5 and 30 minutes, respectively. The highest enhancement occurred at 0.3 kPa, where DO concentrations reached 32.40 mg/L after 5 minutes and 35.34 mg/L after 30 minutes. Table 1 depicts that at oxygen pressures of 0.1, 0.2, and 0.3 kPa, the average DO over 30 minutes was 24.01 ± 4.30 mg/L, 25.30 ± 3.41 mg/L, and 33.83 ± 1.21 mg/L, respectively. There is a sharp increase

in DO in the first 5 minutes at all applied pressures, beyond that, DO rises with a slower rate compared to the initial interval (0–5 minutes). It is expected that with a rise in DO, it tends to saturate in the water.

Table 2. Residual dissolved oxygen (DO) concentration

Time (minutes)	Dissolved Oxygen (mg/l)		
	0.1 kPa	0.2 kPa	0.3 kPa
0	28.80	29.81	35.34
5	25.24	17.67	25.17
30	14.12	13.88	17.57

The stability of the generated oxygen NBs was evaluated indirectly through DO measurements over time. During NB generation ON time, a significant increase in DO concentration at all gas pressures was observed. Thereafter, NB generation was OFF while DO was monitored till 30 minutes (Table 2). Although DO concentrations decreased gradually over time, observed DO values after 30 minutes of NB generation OFF remained substantially higher than the initial condition (2.42 mg/L). The observed DO concentrations were 14.12 mg/L, 13.88 mg/L, and 17.57 mg/L, respectively, for 0.1, 0.2, and 0.3 kPa. This prolonged oxygen retention in the system indicates the presence of stable NBs.

The particle size becomes smaller as the gas pressure increases. It decreases from 170 nm at 0.1 kPa to 93 nm at 0.3 kPa. Smaller NBs are more stable because they have a buoyancy force and more surface effects. Their high internal pressure and large surface-to-volume ratio make them rise more slowly and stay suspended in the liquid for a longer time. The stability of NBs is also related to their surface charge, often described by zeta potential. Studies have shown that NBs usually have a negative zeta potential. This negative charge creates a force between bubbles, preventing them from coalescing.

Although we did not measure zeta potential, the observed persistence of DO supports the presence of stable NBs. Further, the changes in DO levels over time in Table 2 evidence the stability of the NB. The slow decrease in oxygen, especially at higher gas pressures, depicts that oxygen stays in the system for a longer time. This is consistent with the long residence time of NBs, which can remain stable in aqueous systems for extended periods compared to bigger bubbles. Thus, decreasing bubble size enhances physicochemical stability, contributing to improved oxygen transfer efficiency and prolonged DO availability in the system.

The smaller size of NBs greatly increases their total surface area and stability in water, allowing oxygen to dissolve more efficiently. Consequently, systems utilizing NBs achieve a quicker rise in DO levels than those using micro or macro-sized bubbles. In comparison, the use of microbubble nozzles only produces a maximum DO of 8,9 mg/L (I. K. Daging et al., 2022). This indicates that NB technology increases DO levels more effectively than microbubble systems (Budhijanto et al., 2017). According to Laplace's law, as the radius of a bubble decreases, its internal pressure increases, since the internal pressure is inversely proportional to the bubble radius. Due to the

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high internal pressure in small bubbles, the bubbles become unstable and easily disappear. However, in NBs, high internal pressure actually increases oxygen solubility around the bubble interface (Shi et al., 2021). This phenomenon is consistent with Henry's Law, which states that the solubility of a gas in a liquid is directly proportional to its partial pressure (Ferraro et al., 2020). Thus, an increase in gas pressure accelerates the diffusion of oxygen into the liquid and promotes the formation of smaller and more stable bubbles, as seen in the shift in NB size observed in this study. This indicates that gas pressure serves as a critical control parameter for optimizing the DO level through more efficient NBs. By adjusting the pressure, it is possible to generate NBs more efficiently, thereby accelerating oxygen dissolution in the liquid phase.

The high DO concentrations achieved in this study indicate the potential applicability of oxygen NBs for intensive aquaculture systems. Previous studies have demonstrated that enhanced oxygen transfer by NBs can directly improve aquaculture productivity. (Rahmawati et al., 2021) reported that NB in intensive *Penaeus vannamei* culture increased survival rate from 78% to 95%, reduced the feed conversion ratio (FCR) from 1.5 to 1.1, and nearly doubled total harvest and productivity from 222 to 436 kg and from 4.4 to 8.7 kg m⁻³, respectively. These improvements were associated with higher DO concentrations and better water quality conditions maintained by NBs. Similarly, our recent study reported a shrimp survival rate of approximately 99% using the same cartridge NB, indicating the effectiveness of NB-enhanced oxygenation in supporting intensive shrimp culture.

CONCLUSION

The results provide evidence that gas pressure is a critical parameter governing NB formation and size. The effect of gas pressure, evidenced by the reduction in average size from 170 nm at 0.1 kPa to 93 nm at 0.3 kPa, along with a more homogeneous distribution. For smaller NBs produced at a pressure of 0.3 kPa, the DO value increased rapidly in the first 5 minutes to 32.40 mg/L and reached 35.34 mg/L at 30 minutes, confirming that smaller NBs have higher oxygen transfer efficiency. DO level increases rapidly and tends to saturate with time. Gas pressure regulation is an effective approach to optimize NB technology, minimize bubble size, and increase DO levels. The ability to maintain elevated DO levels even after the NB incorporation stopped suggests that continuous aeration can be reduced through NB technology, leading to low operational costs and energy consumption compared to conventional aeration methods, further supporting higher productivity and sustainability in intensive aquaculture systems. Additionally, the enhanced oxygen availability may promote aerobic microbial activity, thereby increasing biological treatment processes and their efficiency in wastewater systems.

This research provides a scientific basis for the development of NB applications in the fields of environment, agriculture, aquaculture, and medicine.

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