Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 2	Month	: April
p-ISSN	: 1693-5462	Volume	: 22	Year	: 2024

Article Processing Dates: Received on 2023-09-05, Reviewed on 2023-09-06, Revised on 2024-01-18, Accepted on 2024-04-15 and Available online on 2024-04-30

Improving the performance of microbubble through the modification and optimization of venturi-type generator

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Abstract

Venturi-type generators are recognized as one of the most promising microbubble generators with potential in various fields. However, there is still room for further optimization of their performance to meet the requirements of real applications, such as aeration systems or water treatment applications. This research modified the geometry of a venturi-type generator with specific dimensions: a length of 80 mm, an inside diameter of 26 mm, a throat diameter of 7.2 mm, a convergent nozzle angle of 30°, a divergent diffuser angle of 30°, and an airflow inlet diameter of 6 mm. By varying the water flow rates (i.e., 22 L/min, 26 L/min, and 30 L/min) and air flow rates (i.e., 0.1 L/min, 0.2 L/min, and 0.3 L/min), the study observed the average diameter, size distribution, Standard Oxygen Transfer Rate (SOTR), and Standard Aeration Efficiency (SAE) of the generated microbubbles. This study aims to improve the performance of a microbubble generator, particularly by optimizing the relative size, distribution, and main parameters for real applications. The proposed modification and optimization successfully produced microbubbles with an average diameter of 180-450 µm. Furthermore, the optimal combinations of water and air flow rates (i.e., 30 L/min of water and 0.1 L/min of air) produced approximately 60% of microbubbles with a diameter of no more than 200 µm. These combinations also enable the delivery of a SOTR and SAE values of 0.94 kgO_2/h and 1.73 kgO_2/kWh, respectively.

Keywords:
Dissolved oxygen, geometry, microbubble, venturi-type generator, water-air flow rate.

1 Introduction

In recent years, microbubble technology has been widely studied for applications in various fields of science and technology, including aeration. In this case, aeration can be determined as introducing air into water using an equipment to ensure the water's oxygen levels reach an adequate level [1]. Microbubbles are gas particles with less than one millimeter diameter that can be evenly distributed in water [2]. Compared to the conventional bubbles with a larger dimension, microbubbles have several advantages such as smaller buoyancy force and a very low speed to the surface, allowing the bubbles to last longer in the water [3]. In addition, microbubbles can provide a more stable interface, larger specific surface area, higher internal pressure, and higher solubility [3, 4]. Microbubbles allow oxygen dissolved in water (Dissolved Oxygen/DO) to last longer, supplying a better oxygen content for respiration and development of organisms in the water [4]. The good increment of DO levels is beneficial to elevate the growth rate of aquatic organisms [5]. Previously, microbubbles were used for water quality treatment and aquaculture in the early stages of their development. In these cases, the Standard Oxygen Transfer Rate (SOTR) and Standard Aeration Efficiency (SAE) are the main parameters determining the performance of microbubble technology. Recently, applications of microbubbles are expanded for various other fields including food technology, medical processing, and mineral mining [6-9].

Microbubble Generator (MBG) is a device to produce bubbles that can be classified into several types such as dissolved air circulation, static mixer, rotary liquid flow, nozzle, as well as venture-type [3, 7]. Until now, venturi has been one of the most developed generators owing to its advantages such as ease of installation and maintenance, fixed internal parts, good reliability, low power consumption, and the avoidance of blockage or contamination during its operation [7, 10]. The traditional venturi generator comprises three main parts: converging, throat, and diverging. Principally, the fluid velocity increases in the throat, whereas the pressure energy is reduced accordingly. In the diverging section, the opposite condition occurs, where the pressure energy is enhanced by the reduction in kinetic energy [7].

The performance of a microbubble generator can be determined by the average bubble diameter, oxygen mass transfer coefficient, geometry, and operating conditions[11, 12]. To improve the performance and efficiency of the venturi-type microbubble generator, many researchers have conducted several strategies such as modifying the geometry of the venturi[4, 13], varying the flow rate[14], and combining it with other types of micro bubble generators[6]. In the last decade, modification of the Venturi geometry and variation in the fluid flow rate have attracted much interest owing to their strong influence on the production of microbubbles[3, 4, 14-17].

There are some variables of the venturi-type geometry that can be modified, such as the convergent angle, divergent angle, throat length, throat diameter, outlet diameter, and inlet air hole diameter. Li et al. (16, 2017) varied the number of inlet air holes and their size in a venturi generator, but no significant effect was obtained [17]. Instead, these studies claimed that the microbubble size would be more affected by the venturi diverging angle. Similarly, Majid et al. (3, 2018)concluded that the Venturi angle is one of the most important factors in a microbubble generator device, which highly influences the bubble size [4]. Previously, it had been stated that the venturi angle with a value of 30° or larger for both inside and outside angle was successfully produced micron-sized microbubbles[3, 18]. Such the angle value of both inside and outside successfully yielded the highest amount of sucked-in air. However, previous studies have not yet used the proper throat diameter because the chosen value was very high (e.g., more than 20 mm). Whereas, throat diameter value is also considered as a critical factor for producing the amount of microbubbles[19]. Vilaida et al. (15, 2019)found that a small throat diameter in a venturi generator could result in more microbubbles than larger ones [16].

In addition, the effect of fluid (i.e., water and air) flow rates in a venturi-type generator is also highly evaluated because of its potential to influence the average diameter and size distribution of the generated microbubbles[7]. It has been stated that the Reynolds number and volume fraction of the liquid greatly affect the microbubble dimensions[14]. In this case, the size of the microbubble was proportional to the airflow rate at a specific water flow value. In contrast, the water flow rate was inversely proportional to the dimensions of the microbubbles obtained [4, 20, 21]. This means that the higher the water flow rate, the smaller the microbubbles that can be produced, and vice versa. Previously, it was concluded that the water flow rate had a significant effect on the microbubble dimension compared to the air flow rate owing to the bubble breakup, which was highly influenced by the turbulence of water flow [22, 23].

A proper combination of the geometric and the flow rates of both the fluids can result in a satisfy performance of the venturi-type generator. There is a chance to improve the performance on venturi type generators hence could deliver an optimum quality especially the average size of the microbubble. In this study, the researcher attempted to develop a new design for venturi-type microbubble generator that can realize abundant microbubbles. The researcher modified the venturi-type generator with appropriate dimensions for both convergent and divergent angles, as well as the diameter of the throat. The variation in the water and air flow rates was then investigated to optimize the produced microbubble. In addition, the Standard Oxygen Transfer Rate (SOTR) and Standard Aeration Efficiency (SAE) of the venturi-type generator were identified to determine its potential for aeration system applications.

2 Research Methods/Materials and Methods

2.1 Experimental Apparatus

A schematic of the apparatus is shown in Fig. 1. Fig. 1(a) shows the concatenation details for the design of the apparatus used in this experiment. Specifically, the Shimizu PC-260 BIT centrifugal pump with a maximum water debit (Qw) value of 30 L/min was utilized to pump the water into a glass aquarium with dimensions of 60 cm × 40 cm × 120 cm. The water content in this experiment was 180 L. Using water as the working fluid, the flow rates (Qw) were adjusted by the pump and measured by the electronic turbine pump K24. Similarly, the air flows (Qg) were also adjusted using a ball valve air controller with a maximum value of 1.5 L/min. Cannon EOS 3000D camera (i.e., 30 fps) was chosen to take videos of the generated bubble. In order to create a clear video capture, A 50W lamp-type OKASIWA IP65 was set in the side of the glass aquarium. AMTAST EC900 DO meter was utilized to measure the production of dissolved oxygen during experiment.

The schematic of the experimental set up p is depicted in Fig. 1(b). Principally, mechanism of the experiment was started by pumping the water from the reservoir with adjustment of the flowing rate. The water flow rate was varied at a certain level (i.e., 22, 26, and 30 L/min), as measured by the electronic turbine pump. In addition, the air flow was also set for three values which was 0.1 L/min, 0.2 L/min, and 0.3 L/min. Such the condition then caused the air to be sucked through the venturi hence producing water with air bubbles. This mixture was then moved to a water tank and captured using a video camera. In order to maintain the same condition, the researcher adjusted the time interval for each fixed variable in the experiment was long enough hence ensuring the previous microbubbles to fully disappear. Measurement of the Dissolved Oxygen (DO) content generated during the operation was also conducted to determine its potential as the aeration technology.

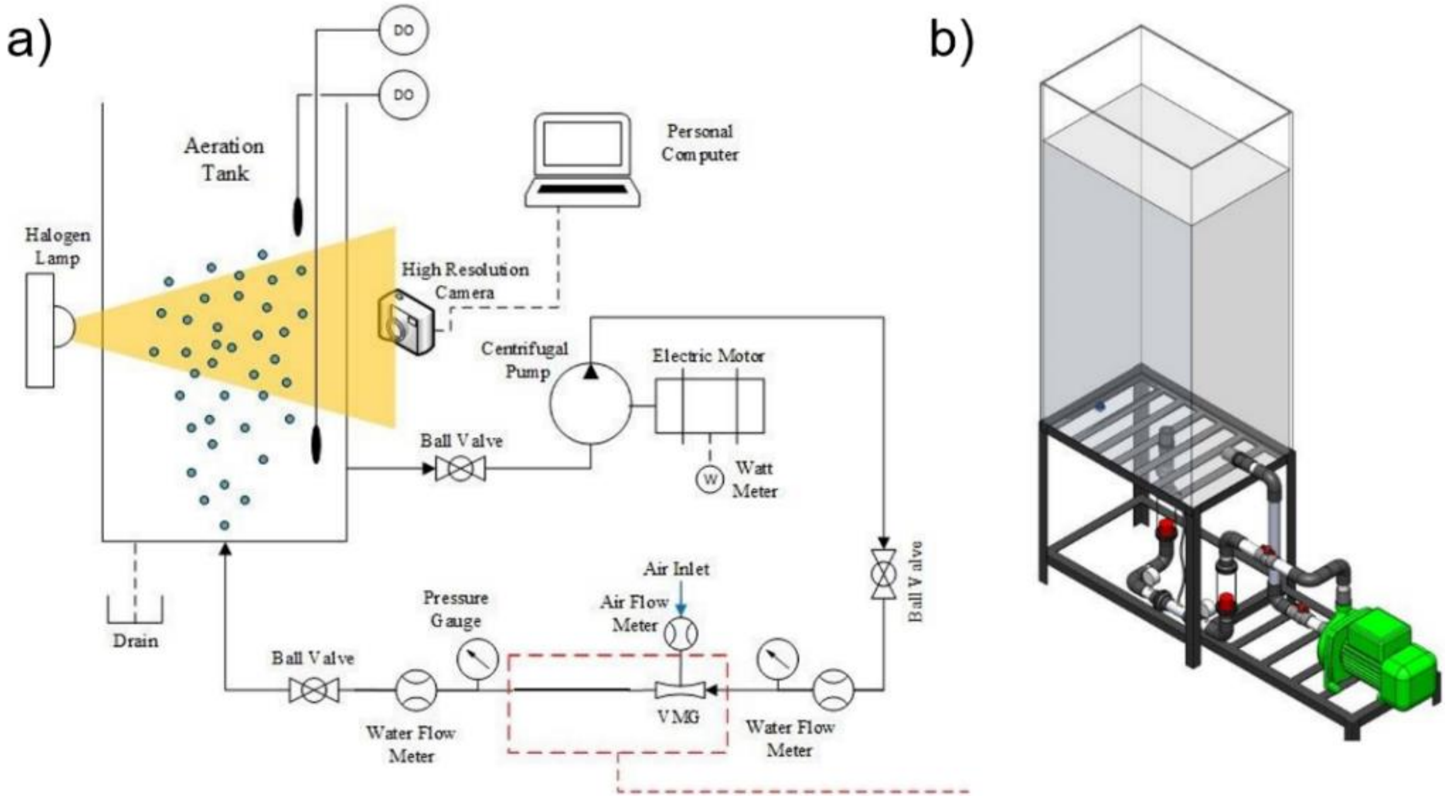

Fig. 1. (a) Detail of the concatenation for design of apparatus and (b) schematic of the experimental set up.

2.2 Images Processing Method

ImageJ software was used to characterize the dimensions of the microbubbles for image processing. Fig. 2 shows the process used to determine the size of the microbubbles using the ImageJ software. The first step in processing the image was conducted by dividing the image into three regions, such as the iteration. Fig. 2(a) shows three regions containing a group of microbubbles for further measurements. Subsequently, the raw image, which was captured using a camera (fps: 30), was converted to an 8-bit type (B/W monotone). The appearance result of such the conversion is displayed in Fig. 2(b). Next, 8-bit (B/W monotone) pictures were converted into black and white images by changing the bubble object in the photo to black, while the background was converted to white. The display of such the black-white mode is shown in Fig. 2(c). In this processing step, measurements of the bubbles were obtained by calibrating the distance using a ruler attached to the glass aquarium. After the microbubbles dimension data were obtained using the ImageJ software, a simple mathematical formula was used to determine the diameter of the microbubbles. Fig. 2(d) shown the result for the measurement of microbubble dimension indicated by the formation of red outer line for each the detected microbubbles.

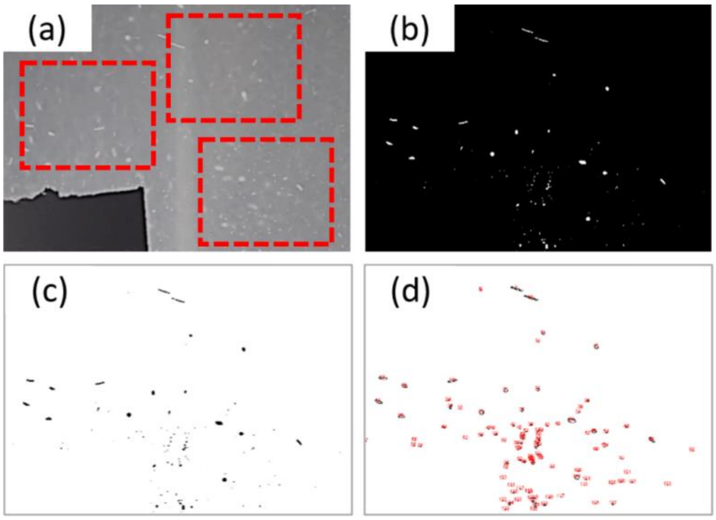

Fig. 2. Steps of the image processing using ImageJ Software. (a) iteration process, (b) 8-bit type (B/W monotone), (c) conversion of 8-bit (B/W monotone) picture into a black and white image, and (d) determination of the diameter of microbubble.

3 Results and Discussion

In this work, microbubble generator was designed using an inlet and outlet angle of 30^{o}. Moreover, a throat diameter of 7.2 mm was selected after a series of literature reviews to improve the production of microbubbles. An engineering image of the developed microbubble is shown in Fig. 3. As can be seen, total length of the venturi generator was about 80 mm with small diameter for the air inlet (i.e., 6 mm). The venturi-type generator was created by 3D printer as the additive manufacturing process using PLA as the raw material. Detail for the dimension of the venturi-type generator as shown in Table 1.

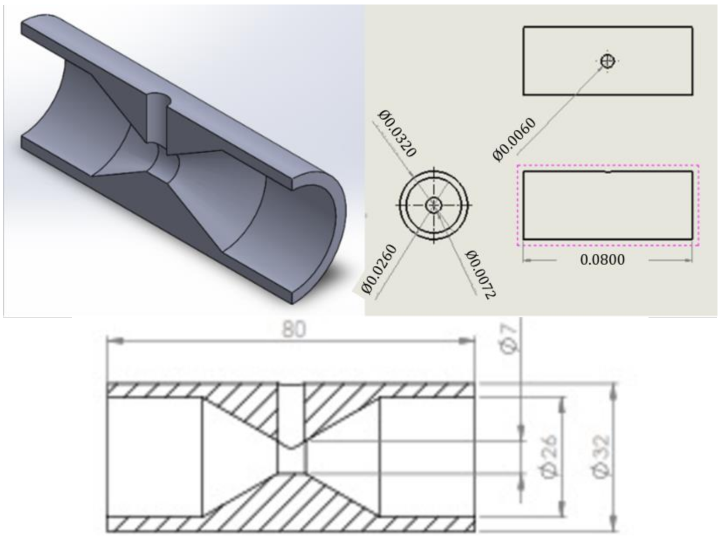

Fig. 3. Design of the venturimicrobubble generator.

Table 1. Specification of the venturi-type generator

Dimension of venturi	Value
Length of venturi	80 mm
Outside diameter	32 mm
Inside diameter	26 mm
Diameter of throat	7.2 mm
Convergent nozzle angle	30°
Divergent diffuser angle	30°
Diameter of the air flow inlet	6 mm

It is known that the combination of the water-air ratio inside the generator highly influences the production of microbubbles; hence, it is important to consider an appropriate combination of air-water flow rates during operation [4]. After the microbubbles were captured and processed to determine their diameter, the researchers attempted to observe the effect of Q_G and $Q_L$on the production of microbubbles. First, the researchers evaluated the effect of the air flow rate on the average diameter of the microbubbles produced. As shown in Fig. 4(a), it is clear that the more air given can result in the wider diameter of the microbubbles. Such a trend is also shown by all the values given for the air flow rates (i.e., 0.1 L/min, 0.2 L/min, 0.3 L/min) for every water flow rate. As the air flow rate increased at a specific water flow value (i.e., 22 L/min, 26 L/min, and 30 L/min), it was clearly seen that the diameters of the produced microbubbles also increased, which was attributed to the higher air flow rate that was sucked into the venturi-type generator. The main reason for this is that a higher air flow rate yields a higher number and density of microbubbles, which may lead to a higher probability of bubble coalescence. Moreover, once the airflow rate increased, more air was sucked into the generator. This lowers the liquid energy obtained per unit gas, which may lead to a lower energy of bubble breakup.

In contrary, Fig. 4(b) shows that the diameter of microbubbles decreased as the water flow rates increases. The researchers believe that the increase of water flow rate caused higher velocity of water. Such a condition effectively reinforces the inertia effect during the production of microbubbles, thereby reducing the surface tension and relative diameter of the bubbles produced[24]. Another explanation concludes that the larger water flow rate can result in more turbulence in the air-water flow, causing the bubbles easier to be dispersed in the form of small bubbles [4]. The plotting data elucidates that venturi-type generator in this research can produce microbubbles with average diameter of 180-450 μm. The smallest average diameter of the microbubbles in this research at about 180 μm was obtained from the combination of water and air flow rate of 30 L/min and 0.1 L/min, respectively. Impressively, such the value is better compared to the other work that used similar inlet and outlet angle but in high water flow rate (i.e., 140-220 L/min) [3]. Researchers believe that such good performance can be attributed to the small diameter of the throat part, which enables the production of small microbubbles.

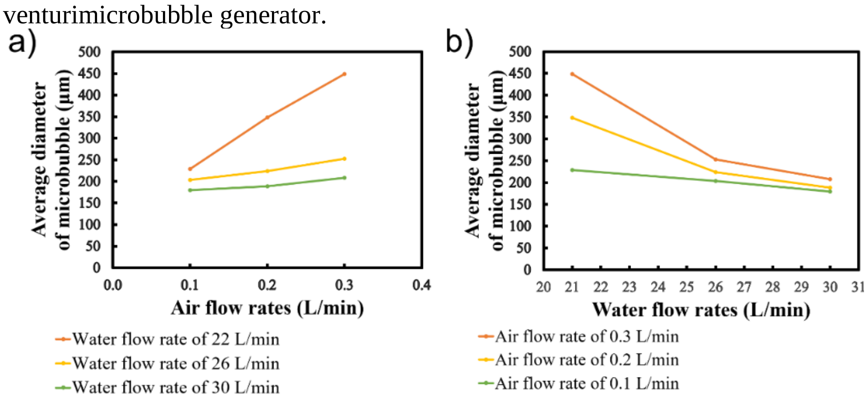

Fig. 4. The effect of (a) air flow rates and (b) water flow rates toward the dimension of microbubble.

In addition to the size of microbubble, number of the produced microbubble is also considered as another important parameter that must be evaluated. Fig. 5(a) – Fig. 5(c) shown the trend of microbubble production in different water flow rate. As can be seen in Fig. 5(a), increasement trend for the microbubble production can be obtained toward the air flow rates given. Despite the anomaly trend was found in the air flow rate of 0.2 L/min, the positive linear trendline should be obtained inside the graphic clearly (Fig. 5(a)). Moreover, such the positive linear trendline for the production of microbubble caused by the high air flow rate is also supported by other measurement that provide R-squared value as high as 0.9 (Fig. 5(b) and Fig. 5(c)). This indicates that an increase in the airflow rate is beneficial for enhancing the production of microbubbles. However, it must be considered that improvement of the quantity of microbubble through the high air flow rate will also result in bigger size of the dimension.

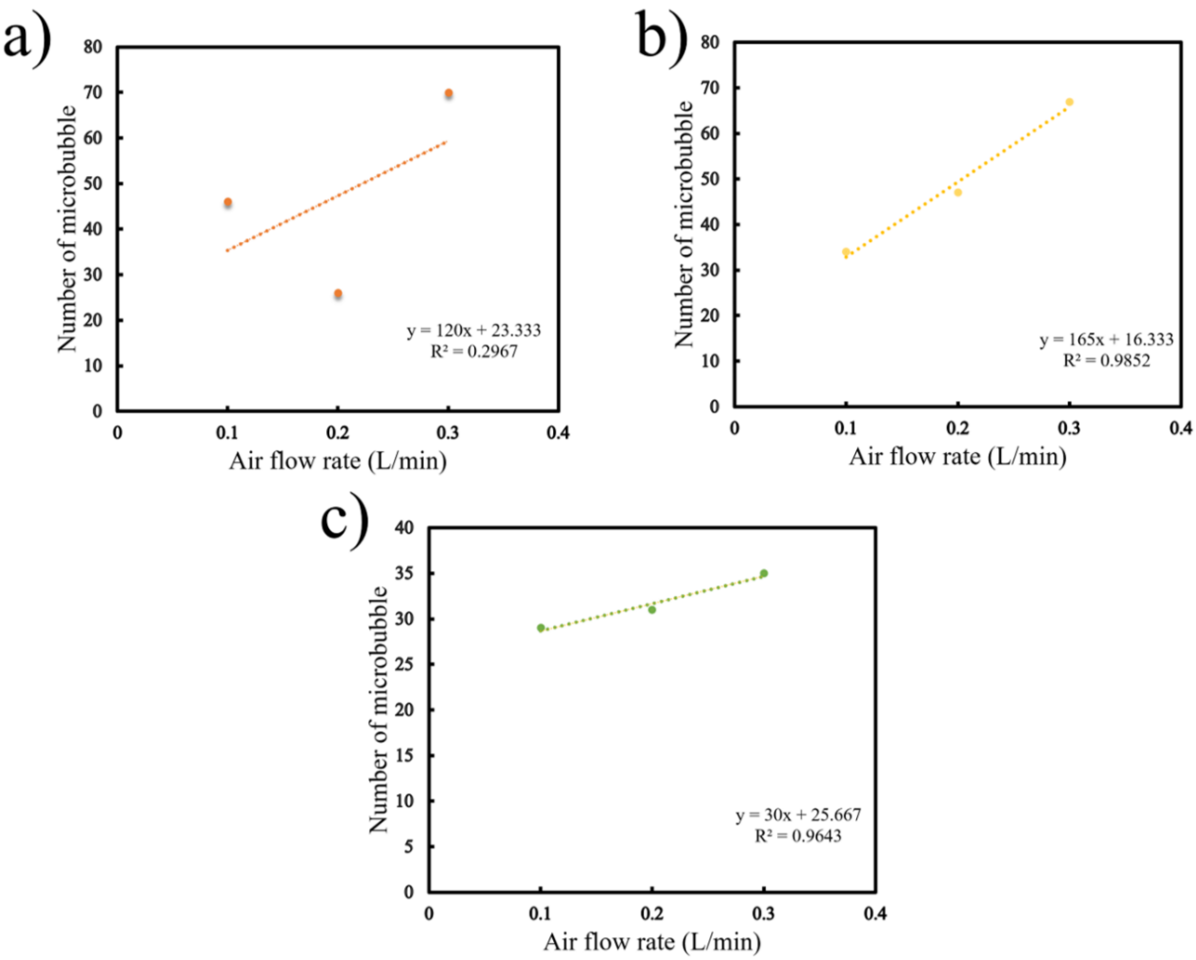

Fig. 5. Trends for the production of microbubble caused by the air flow rate given in the water flow rate of (a) 22 L/min, (b) 26 L/min, and (c) 30 L/min.

Observation for the microbubble distribution was then carried out in the form of Probability Density Function (PDF), which is one of most commonly used of statistical techniques due to its practicality and accuracy [25, 26]. It was seen that increasement of the water flow rate could result in homogeneously bubble size distribution (Fig. 6(a) – Fig. 6(c)). In contrary, the larger air flow rate given to the venturi-type generator causes the bubble distribution to be more prevalent. Those phenomena can be attributed to the coalescence and break up mechanism which can affect to the generation of shear effects and bubble instabilities [4]. The proposed air discharge of 0.1 L/min shows better results compared to the other input air discharges. The best PDF value in this experiment occurs in the water discharge test parameter of 30 L/min and the input air of 0.1 L/min with a value of 0.44.

In particular, the researchers also investigate the distribution of microbubble size toward the combination that result in the smallest average dimension in this work (Fig. 6(d)). The researchers evaluated the distribution of the microbubble size in three regions of the photo captured. As the result, the combination of 30 L/min water flow rate and 0.1 L/min air flow rate provides a good possibility to produce small size microbubble. In particular, ~60% of the microbubble with a diameter no more than 200 μm can be produced such by the combination. It is clearly seen that as the treatment potential to generate abundant bubbles with small buoyancy force and low speed to the surface hence allowing the produced bubbles to last longer in the water.

The Standard Oxygen Transfer Rate (SOTR) as an important parameter in this experiment indicates the rate at which oxygen is transferred into the water. The SOTR graphic in Fig. 7 clearly shows an increasement as the water flow increases and the input air flow decreases. Combination of the water flow discharge at 30 L/min and the input air of 0.1 L/m provides the highest SOTR with a value of 0.94 kgO_2/h. This fact can be caused by the smaller bubble size obtained which is able to increase the rate of oxygen transfer into the water due to the more stable interface, large specific surface area, high internal pressure, and high solubility [4, 6].

Similarly, efficiency of the aeration system is determined by calculating the Standard Aeration Efficiency (SAE) which is the ratio between the Standard Oxygen Transfer Rate (SOTR) and the input power of the electric motor pump. The SAE value from the measurement (Fig. 8) shows a pattern similar to that the SOTR graph. It is clearly seen that the SAE value is proportional to the increasement of water flow and decrease in the air flow. This can be caused due to the input power of pump which has an average input power for the three variations. The combination of water discharge at 30 L/min and 0.1 L/min of air flow rate results in the highest SAE value of 1.73 kgO_2/kWh.

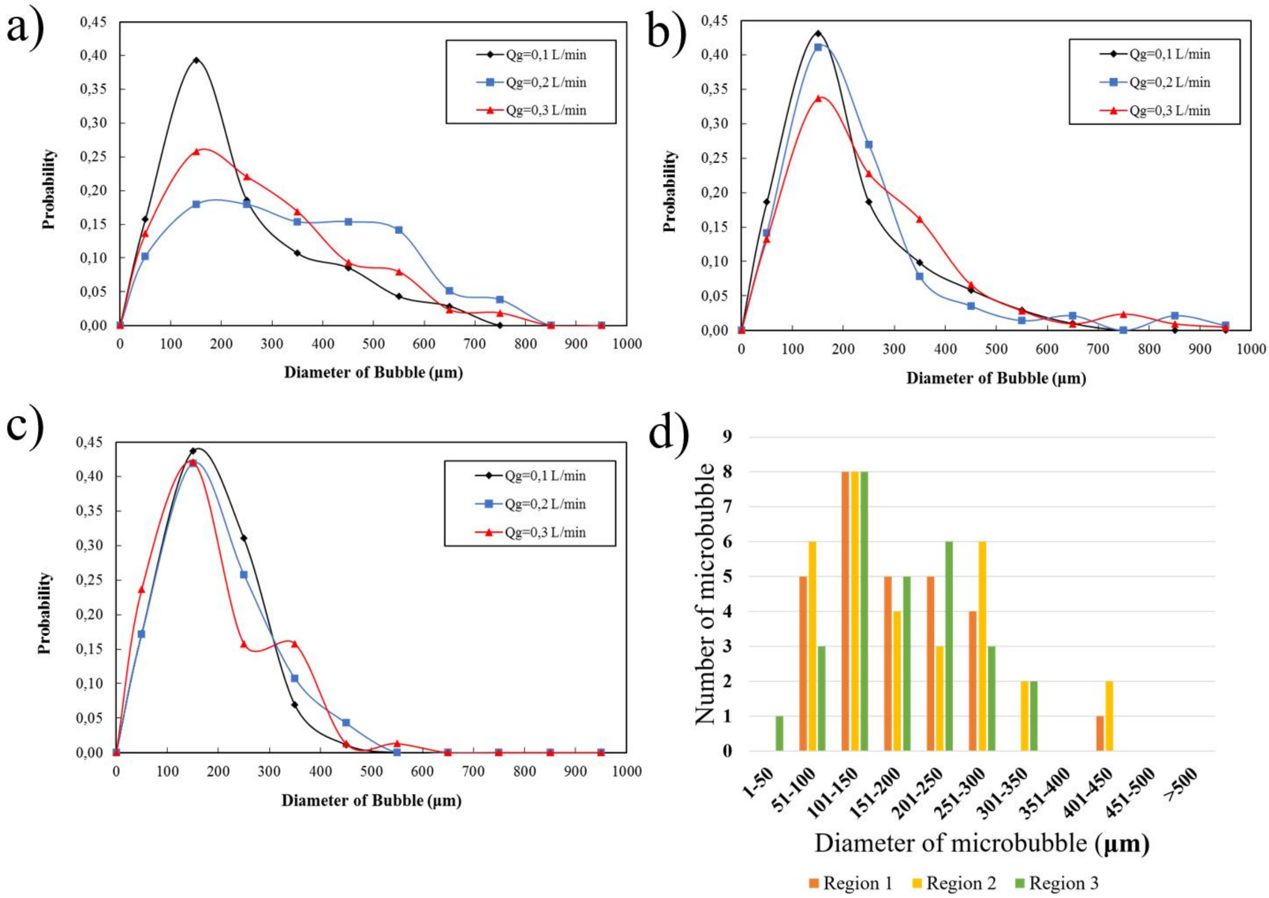

Fig. 6. Measurement of the probability microbubble size caused by the air flow rate given in water flow rate of (a) 22 L/min, (b) 26 L/min, and (c) 30 L/min. (d) Distribution of microbubble size generated from the combination of water discharge at 30 L/min and 0.1 L/min of air flow rate.

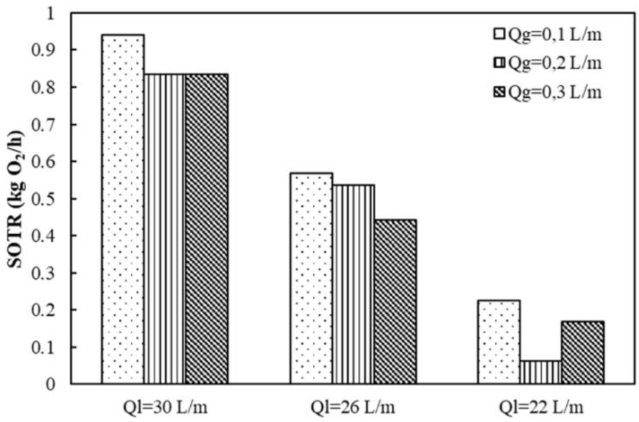

Fig. 7. Evaluation of the Standard Oxygen Transfer Rate (SOTR) from the venturi-type generator.

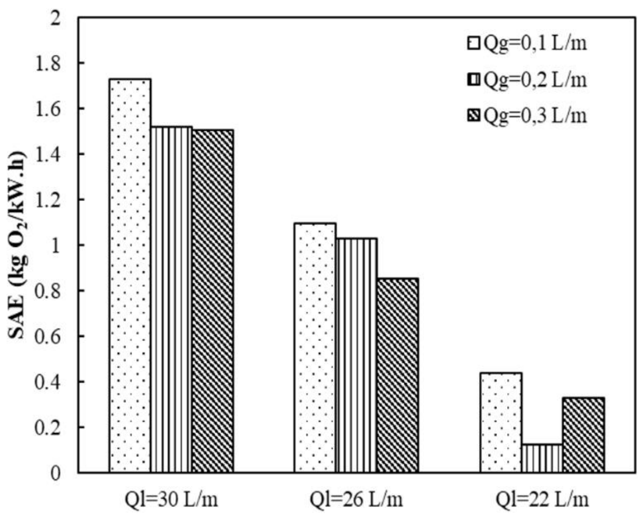

Fig. 8. Evaluation of the Standard Aeration Efficiency (SAE) from the venturi-type generator.

4 Conclusion

Venturi-type generator is one of the most promising microbubble technologies for generating small bubble with good quality and quantity. In this case, average diameter and distribution of the microbubble dimension are used as the main parameter to determine the performance of generator. The researcher evaluated the effect of flow rate (i.e., air and water) given to the proposed geometry of the venturi-type toward the produced microbubble. It can be seen that such the treatment success to produce microbubble with average diameter of 180-450 µm. It is clearly seen from the trend that the more air given will result in the wider diameter of the microbubble. On the other hand, the dimension of microbubble decreased as the increasement of water flow rates given. The combination of water and air flow rate of 30 L/min and 0.1 L/min in this work success to generate ~60% of microbubble with the dimension no more than 200 µm. The best combination of water-air flow rate in this work is able to obtain SOTR and SAE value of 0.94 kgO_2/h and 1.73 kgO_2/kWh, respectively.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors acknowledge the funding support from the Ministry of Marine Affairs and Fisheries of the Republic of Indonesia through DIPA 2021.

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