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Paper:

A Collector of Dissolved Air Using Centrifugal Separation for Underwater Breathing

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This paper investigates a novel underwater breathing apparatus which has no air tank. Instead, it uses centrifugal separation to collect dissolved air. First, a prototype collector is proposed and fabricated. Then, the basic characteristics of various shape parameters are experimentally investigated using tap water to ascertain the optimal design. Next, to confirm the validity of the proposed mechanism, CFD analysis on collection ratio is done using the commercially available STAR-CD tool. After that, a suction device without an additional power source is developed to improve the air collection ratio. Finally, the redesigned collector is tested at different water temperatures, and the air collection results obtained are compared with the results of analysis.

Keywords: underwater breathing, dissolved air, centrifugal separation, collector, differential pressure

1. Introduction

Deep and lengthy underwater diving activities have been an important subject in military science and fishery policies since ancient times. Free diving (breath-holding) activities without the aid of mechanical devices were restricted to relatively shallow depths and usually involved the use of additional units, such as hollow reeds or leather breathing bladders, in ancient times [1].

Nowadays, SCUBA (Self-Contained Underwater Breathing Apparatus) diving [2], which involves the use of a tank of compressed air and a regulator, enables one to stay under water for about 30 minutes, although the diving time depends upon the depth, tank volume, and diver's air consumption ratio. A standard air tank for an average diver is made of aluminum and has a volume of 80 cubic feet. Although scuba divers carry their air supply with them under water, both sea water and fresh water contain dissolved air. Generally, human beings require at least 1 liter of oxygen per minute to carry out underwater activities. Therefore, underwater breathing needs more than 5 liters of air per minute. This is because it has been ascertained that the atmosphere is 21% oxygen. However, water is about 34.5% oxygen.

Recently, artificial gills employing hollow fibers or functional membranes for gas filtration have been investigated to enable humans to breathe under water as a fish does, without the use of an aqualung [3–8]. These artificial gills have the benefit of enabling extended dive times without the necessity of an additional air tank. However, no commercially available products have resulted from the above research studies because of the low efficiency of dissolved air extraction and the large size of the equipment. At the same time, a method of using centrifugal separation to extract dissolved air from water was proposed by an Israeli inventor, A. Boner [9], but its development is still at the prototype stage, and the authors have not found further research results. In other research, R. Suzuki and Y. Tanaka used the swirling flow resulting from centrifugation to eliminate bubbles in hydraulic systems [10–13]. Their proposal has some advantages: a smaller oil reservoir, a drop in oil temperature, and an increase in pump efficiency, among others. Bubbles and dissolved gases in oil greatly affect the performance of fluid power systems because of cavitation, aeration inception, degradation of lubrication, noise generation, and oil temperature rise [14]. However, the above studies were limited to hydraulic systems. Therefore, we have proposed and investigated a novel underwater method for breathing without an air tank in fresh or salt water [15]. It employs a mechanism similar to the above-mentioned bubble eliminators [10–13]. We expect it to enable people to dive for extended periods of time with lighter equipment.

In this study, a novel collector of dissolved air, one that uses centrifugal separation, is investigated for underwater breathing without an air tank. First, a prototype collector is proposed and fabricated. Then, tests are run using tap water to investigate its basic characteristics. Second, to confirm the validity of the proposed mechanism, CFD analysis on the collection ratio is done using the commercially available STAR-CD tool. Furthermore, a collected

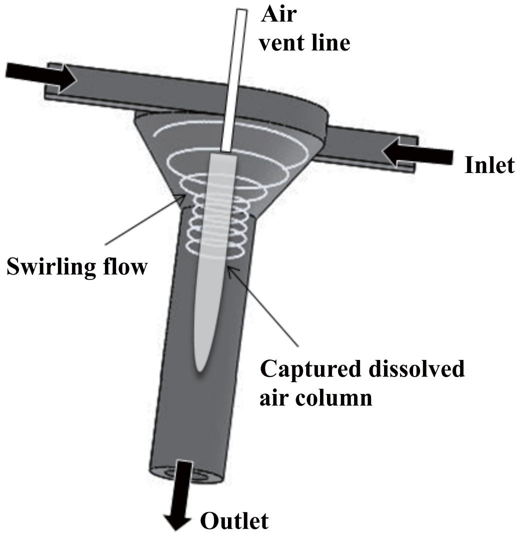


Fig. 1. Schematic of collector using centrifugation.

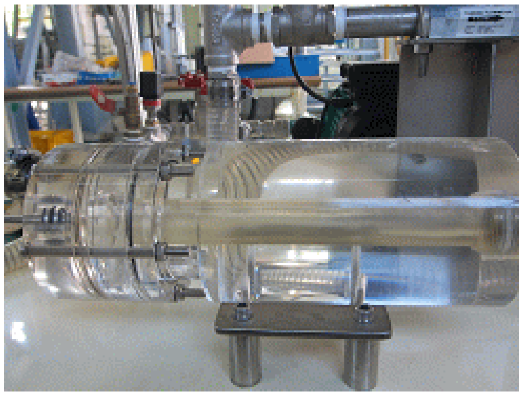


Fig. 2. Fabricated prototype collector.

Fig. 3. Constructed experimental apparatus.

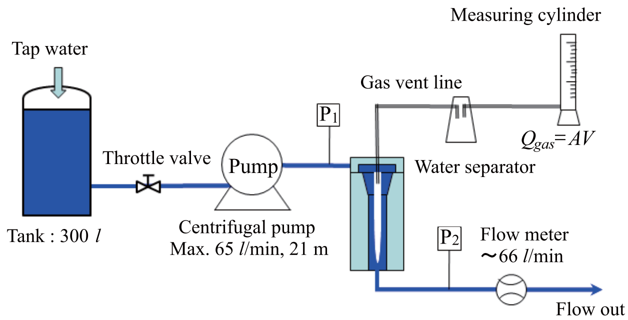


Fig. 4. Schematic of the experimental apparatus.

air suction device that does not use an additional power source is developed to improve the collection ratio. Finally, the basic characteristics of the redesigned collector are tested at different water temperatures, and the experimental results obtained are compared with the analysis results.

2. Centrifugation Type Collector

2.1. Design and Fabrication

Figure 1 shows our proposed collector, which uses centrifugal force. It is basically composed of three parts: an inlet connected to an external pump to supply fresh or salt water, a tapered part with an oblique section to generate a swirling flow, and an outlet with a straight tube. In this study, dissolved air is transformed into bubbles by means of cavitation. The cavitation results from a drop in pressure through a throttle valve between pump and tank. The dissolved air, now in the form of bubble, is led to an inlet of the collector. Air bubbles of low specific gravity are collected in the axial center due to the high velocity of the swirling flow. The captured air bubbles accumulate near the end of the tapered chamber where the pressure is lowest. Then, the air bubbles join to become a large column of air bubbles [12–13]. This collected column of air bubbles flows out through a vent line [15]. **Fig. 2** shows a prototype fabricated from acrylic to make the process visible. The diameter of the tapered part, which has an oblique section, is 28 mm at the inlet and 20 mm at the outlet, and the length of the taper is 22.7 mm. The length of the straight tube is 213 mm.

2.2. Experiments with Design Parameters

First, the basic characteristics were investigated experimentally using tap water and a centrifugal pump (a WILO, PB-350MA, having a maximum flow rate of 65 *l*/min, and a maximum head of 21 m). **Figs. 3** and **4** are a photograph and a schematic, respectively, of the experimental apparatus constructed for investigating the fabricated prototype collector. Two pressure transducers were installed to measure a differential pressure in the front and rear parts of the collector. In advance, a soap bubble was formed in the measuring cylinder. The captured air moved into the bottom of the cylinder through a vent line. The surface of the soap bubble gained height as the volume of captured air increased. Here, the flow rate of the extracted air was calculated by measuring the speed of the surface of the soap bubble in the cylinder. The collector was also designed to employ an impeller to facilitate the swirling flow, as shown in **Fig. 5**.

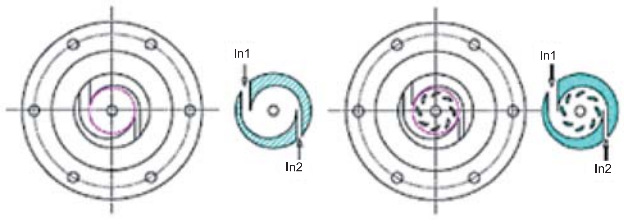


Fig. 5. Schematic of the designed impeller.

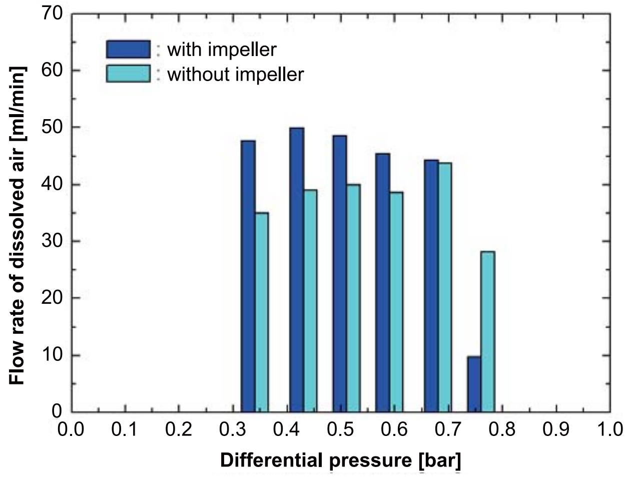


Fig. 6. Experimental results with/without impeller.

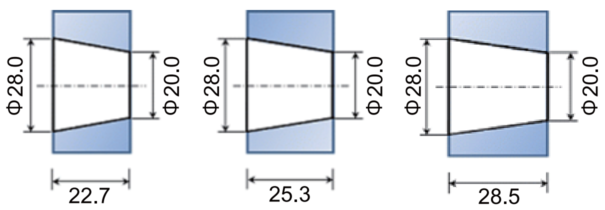


Fig. 7. Various chamber parameters for swirling flow.

Experiments were conducted to find the flow rates of captured air at different pressures, and the results are presented in **Fig. 6**. An air bubble column was not generated due to low centrifugal force in lower range of differential pressure. On the other hand, collected air could not be extracted due to the inner pressure change of the collector in the higher range of differential pressure. The collector had better performance with the impeller than without it, although both sets of results showed similar characteristics. The flow rate of the dissolved air captured was 50 m*l*/min with a differential pressure of 0.43 bar and a water flow rate of 18.7 *l*/min.

The parts tapered to generate a swirling flow caused by centrifugal force were redesigned as shown in **Fig. 7**. The results of tests on the flow rate of the captured air are given in **Fig. 8**. Air bubbles were collected within a certain range of the differential pressure, similar to the range in the results column above. The results confirmed that a length of 25.3 mm had the best performance: the flow rate of captured air was 65 m*l*/min with a differential pressure of 0.52 bar. In general, the percentages of oxygen are 34.4% in fresh water and 34.8% in sea water. Oxygen solubility is 6.8 m*l* per liter at 20°C in fresh water at atmosphere pressure. The amount of dissolved gas, including N_2, CO_2, Ar, and others, is assumed to be 19.8 m*l*/liter under the same conditions. Therefore, it can be assumed that the collection ratio of captured dissolved air, 65 m*l*/min, was about 16.4% of the theoretical value, 396 m*l*/min, in this experiment with a 20 *l*/min of water.

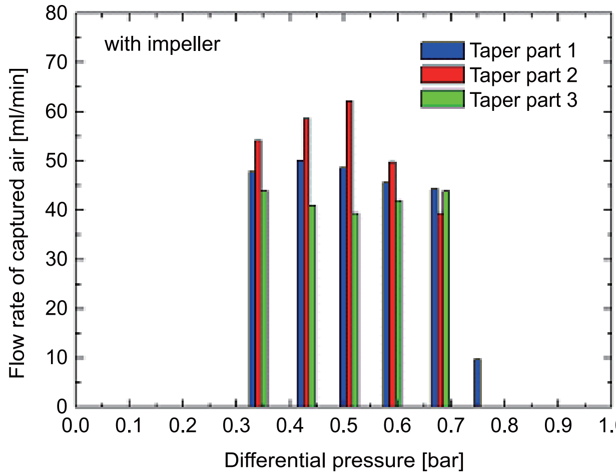


Fig. 8. Experimental results with various chamber parameters.

2.3. CFD Analysis

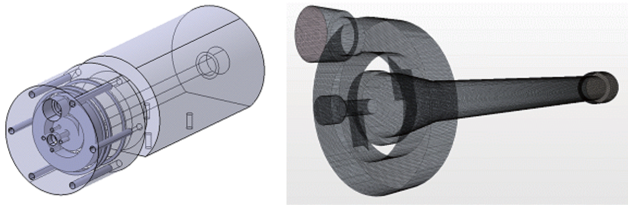
To verify the validity of development because of the low collection ratio, CFD analysis using the commercially available STAR-CD tool with the dimensions of the prototype model was performed. The flow rate and dissolved air ratio were 180 *l*/min and 3.5% (6.3 *l*/min), respectively.

In this analysis, two models were used, one with and one without an impeller to assist the flow in the swirling part. **Figs. 9** and **10** show the analysis results obtained after 0.1 sec for each. The results confirm that the model without the impeller presents an effective air distribution and smooth flow. **Fig. 11** compares collection ratio results. The highest collection ratio of 56% was obtained without the impeller.

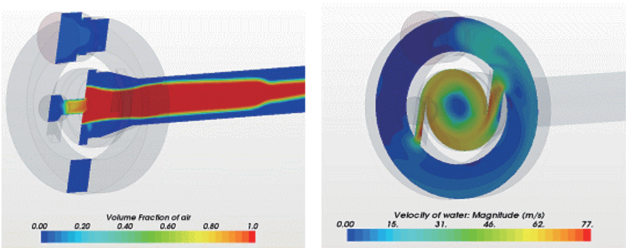
3. Structural Improvement

3.1. Proposal of Air Suction Device

The collected air was extracted using a straight tube with an inner diameter of 4.0 mm in experiments using the fabricated prototype. To improve the collection ratio based on the analysis results obtained, an air suction device without an additional power source was proposed as shown in **Fig. 12**. The lower vane is rotated by the swirling flow that results from centrifugal force. The connected upper fan is also rotated in line with the lower vane.

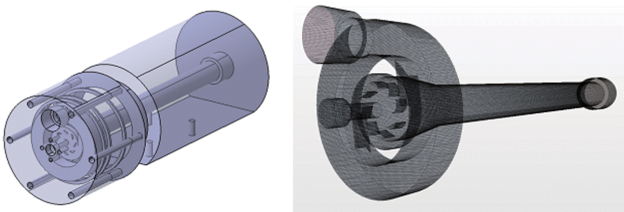


(a) CATIA model (b) Grid: trimmed mesh

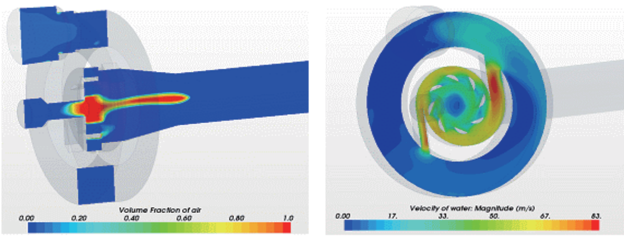


(c) Air distribution (d) Velocity of water

Fig. 9. Analysis results: impeller not used.

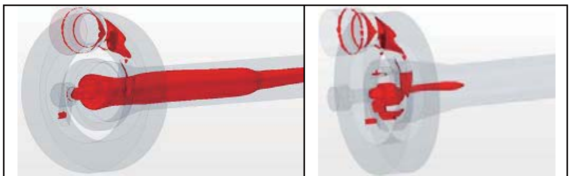


(a) CATIA model (b) Grid: trimmed mesh



(c) Air distribution (d) Velocity of water

Fig. 10. Analysis results: impeller used.



Captured air : 3.5 *l*/min	0.55 *l*/min
Collection ratio : 56%	9%

(a) Without impeller (b) With impeller

Fig. 11. Compared analysis results: collection ratio.

Therefore, the collected air is forced out. **Fig. 13** shows a 3D model and a photograph of the fabricated device.

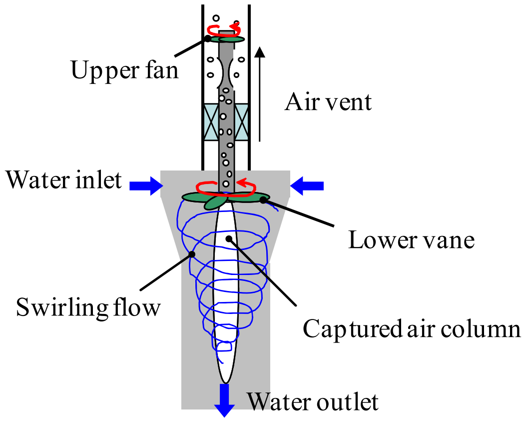
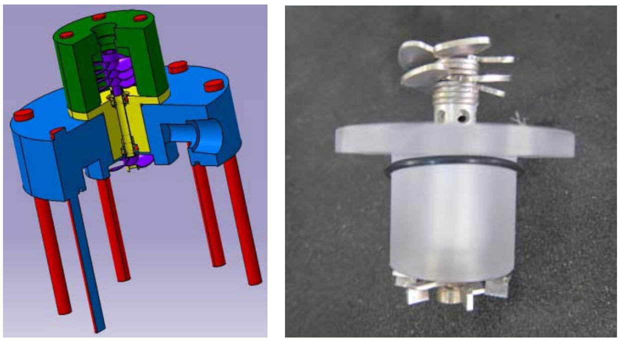


Fig. 12. Concept of the air suction device.



(a) 3-D model (b) Photograph

Fig. 13. Fabrication of the air suction device.

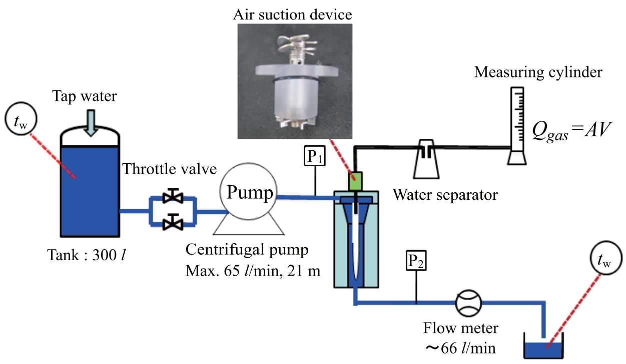


Fig. 14. Schematic of the reconstructed experimental apparatus using air suction device.

3.2. Experiments with Air Suction Device

Figure 14 is a schematic of the reconstructed experimental apparatus using the air suction device. Tap water was pumped into the collector through the throttle valves. Here, the valves were employed to effectively use cavitation to generate air bubbles. Then, a flow meter was used to measure the flow rate of the tap water. **Fig. 15** is a photograph of the experimental apparatus. The basic characteristics of the redesigned collector were tested at different water temperatures. **Fig. 16** shows the results obtained. It was ascertained that a column air bubble was

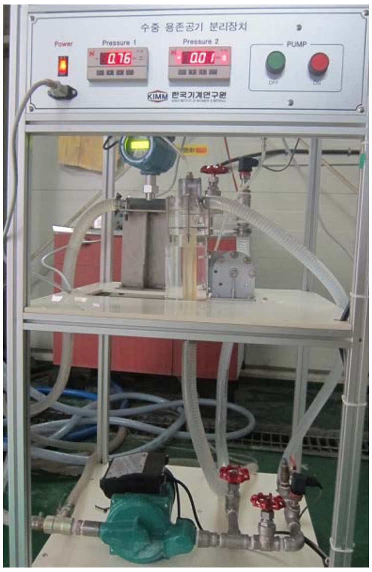


Fig. 15. Experimental setup.

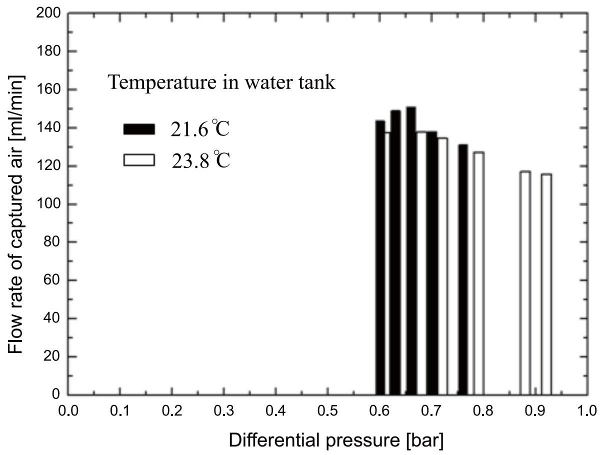


Fig. 16. Experimental results of the dissolved air captured at different water temperatures.

also generated in certain differential pressure ranges. The experiments confirmed that low water temperature yields better performance in terms of the quantity of air captured because cold water holds a higher quantity of dissolved air. The flow rate of captured air was 151 m*l*/min with a differential pressure of 0.66 bar and a water flow rate of 17.3 *l*/min. Oxygen solubility is 6.6 m*l* per liter at 21.6°C in fresh water, and dissolved air was assumed to be 19.2 m*l*/min. Therefore, it can be assumed that the collection ratio of dissolved air is about 45.5% in this experiment. It can also be assumed that the flow rate of captured air is 138 m*l*/min with a differential pressure of 0.61 bar and a water flow rate of 15.6 *l*/min. Considering oxygen solubility at 23.8°C, it can be assumed that the collection ratio of dissolved air is about 47.6%. These experiments verified that the proposed air suction device improves the collection ratio of dissolved air.

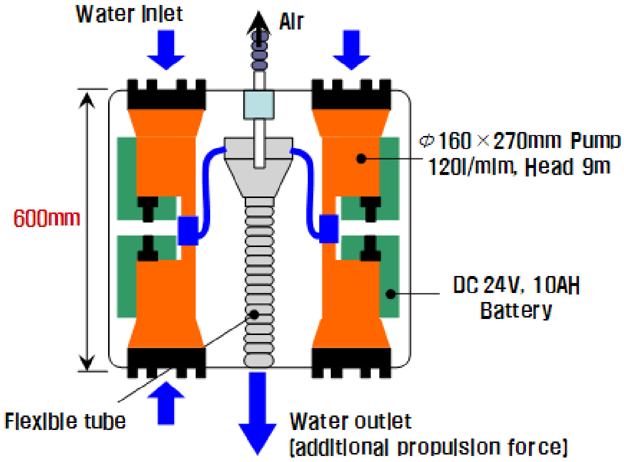


Fig. 17. Future work concept of portable equipment for underwater breathing.

4. Conclusions

In this study, a novel collector of dissolved air using centrifugal separation for portable underwater breathing equipment without air tanks was proposed. Analytic study and experimental results with some structural improvements were presented to verify the development. The results showed that dissolved air was captured at the rate of 138 ml/min at a water temperature of 23.8°C, and the collection rate was 47.6%. Results of collection ratio obtained from the experiment and analysis show similar values.

Figure 17 shows a concept of a portable backpack type of device for underwater breathing, the subject of future work. The total weight of the equipment is assumed to be 40 kg with four pumps, four batteries, and so on. The optimal structure will need to be further considered if the collection aim of 5 *l* of dissolved air per minute is to be attained.

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