

Design and performance of honeycomb structure for nanobubbles generating apparatus having different cell dimensions

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Abstract. In recent years, nanobubble technology has drawn great attention due to their wide applications in various fields of science and technology, such as water treatment, biomedical engineering, and nanomaterials. This study focuses on the application to seafood long term storage. The nitrogen nanobubble water circulation may reduce the oxygen in water and slow the progressions of oxidation and spoilage. Our previous study showed the pressure reduction and shear stress are involved in nanobubble generation apparatus with honeycomb cells. In this work, the nanobubble generating performance is studied experimentally for honeycomb structures by varying the cell size and the flow velocity. Computational Fluid Dynamics analysis is also performed to simulate the experiment and find out the efficient nanobubble generation.

1. Introduction

In recent years, nanobubble technology has drawn great attention due to their wide applications in wide fields of science and technology, such as water treatment, medical engineering, and chemical and food industry. Among them, this study focuses on the application to seafood long term storage. The nitrogen nanobubble water circulation may reduce the oxygen in water and slow the progressions of oxidation and spoilage [1,2]. In this study, we mainly focus on the technique of honeycomb structure which have excellent efficiency of nanobubble generation [2-4].

Our previous study showed the pressure reduction and shear stress are involved in nanobubble generation when a large apparatus in figure 1(a) is used for 1000 liters of water [3-5]. In this study, a small apparatus in figure 1(b) will be used for 100 liters of water in comparison with the large apparatus under different cell size and fluid velocity. Experimental studies will be conducted to investigate the nanobubble generating performance in honeycomb structures by varying the cell size and the flow velocity. The design and performance of the honeycomb structures will be discussed to generate nanobubble efficiently.

2. Nanobubble generation experiments

Figure 1 shows the experimental apparatus with parallel honeycomb units immersed in water in a



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container and table 1 shows the details of the experimental apparatus. The water and the nitrogen gas are pumped into this apparatus together flowing into the honeycomb units. Figure 2 shows the model of the honeycomb structure consisting of a pair of honeycomb plates and upper and lower plates for sealing both ends. Through the complex flow channels composed by the overlapped honeycomb plates, the turbulence for the gas-liquid mixture may generate nanobubbles. During many times of the gas-liquid mixture flow from a wide area to a narrow area, the shear field and the pressure reduction are formed many times, which contribute to the nitrogen bubbles finer. This cycle has been repeated, and miniaturization effect continues. The experimental conditions are shown in table 2.

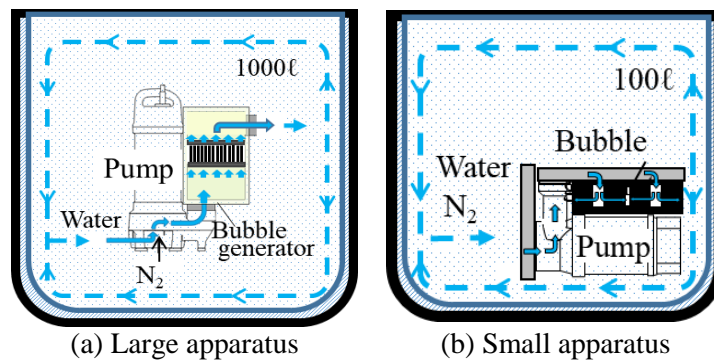


Figure 1. Nitrogen nanobubbles generating apparatus.

Table 1. Details of the experimental apparatus.

Item	Large apparatus	Small apparatus
Pump	Submersible pump (80TM23.7)	Submersible pump (50TML2.4S)
Output [kW]	3.7, (60 Hz)	0.4, (60 Hz)
Flow rate [ℓ/min]	400	270
Container [mm]	1580×1100×600	840×600×500
Water amount [ℓ]	Tap water, 1000	Tap water, 100
Gas	Nitrogen	Nitrogen
Flow rate [ℓ/min]	5.0	1.0
Pressure [MPa]	0.30	0.20

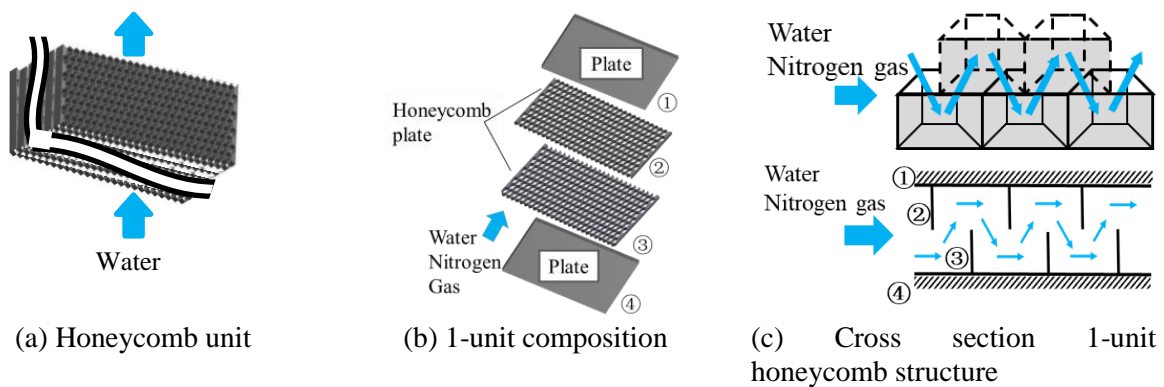
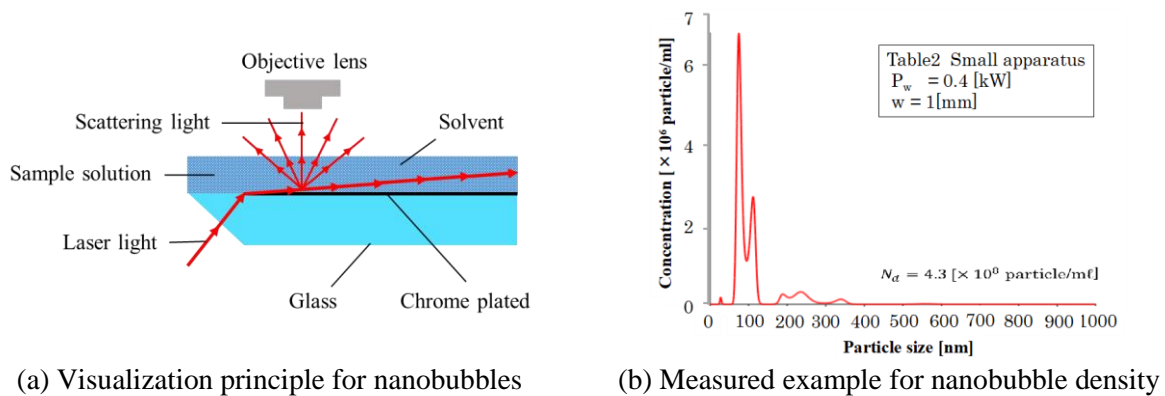


Figure 2. Honeycomb structure model of generating apparatus.

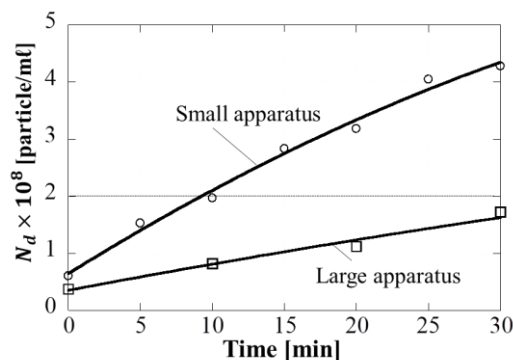
Table 2. Experimental condition.

Experimental conditions	Power [kW]	Wall Thickness [mm]	Inlet Pressure [MPa]	Flow rate [ℓ/min]
Large apparatus	3.7	0.5	0.35	550
Small apparatus	0.4	1	0.06	103

**Figure 3.** Visualization principle and measured example for nano sight.

The nano-particle analyzer, Nano Sight LM10-HS [6], is used to measure the nanobubble number density. Figure 3(a) shows the principle of Nano Sight LM10-HS. Irradiating a laser beam in the horizontal direction in the sample liquid, the side-scattered light from the nanoparticles are visualized by the objective lens, the movement trajectory of each particle is displayed on computer. Tracking Brownian motion of all particles recognized on the screen and using the Stokes-Einstein equation, the particle size is obtained from the moving velocity of the particles. Figure 3(b) shows an example of the nanobubble number density distribution measured at 60 minutes after the start of the experiment. After collecting the sample solution, measure the nanobubble number density within the range of 30 minutes to 1 hour at which micro bubbles of 1 μm or more disappear and become stable state.

Figure 4 shows the time variation of nanobubble number density for large and small apparatus. The target value was set to a nanobubble number density of 200 million / ml whose effect was confirmed by sensory test using fresh fish. It can be seen that the small apparatus achieves the target value after 10 minutes and then the nanobubble number density further increases. Compared to the experimental results of large apparatus obtained in previous studies, better nanobubble number densities can be obtained for the small apparatus, although the water amount, pump output, etc. are smaller than the ones of the large apparatus.

**Figure 4.** Time variation of nanobubble number density.

3. CFD analysis

Figure 5 shows (a) flow direction, (b) contour plot of velocity and (c) contour plot of shear stress in a honeycomb cell of the small apparatus. Considered flow Path 1-Path 6 are also indicated. The results in figure 5 are obtained under the inlet pressure shown in table 2 with the cell dimensions in table 3.

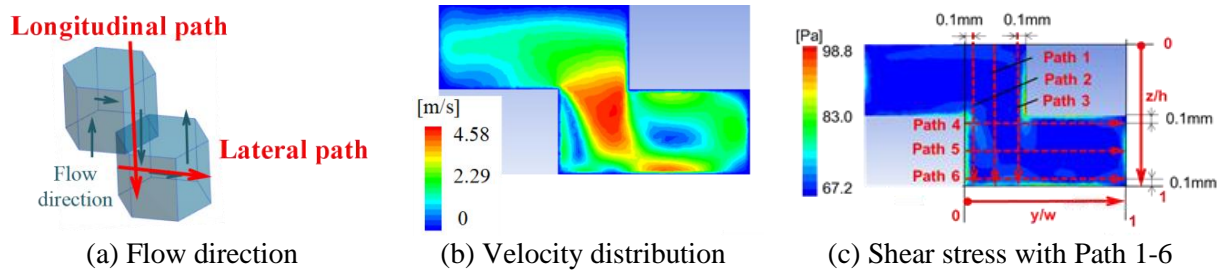


Figure 5. Schematic illustrations of flow direction, velocity distribution and shear stress with Path 1-6.

Table 3. Experimental results.

	Item	Large apparatus	Small apparatus
Conditions	Cell width [mm]	6.1	3.9
	Cell height [mm]	10	4.0
	Flow rate [ℓ/min]	550	103
	Water amount [ℓ]	1000	100
	Number of cells	3510	1840
Performance	Nanobubble number density after 30 min [particle/ $\text{m}\ell$]	1.7×10^8	4.3×10^8
	Nanobubble number density per cell per cycle [particle/ $\text{m}\ell$]	3.13×10^3	7.61×10^3

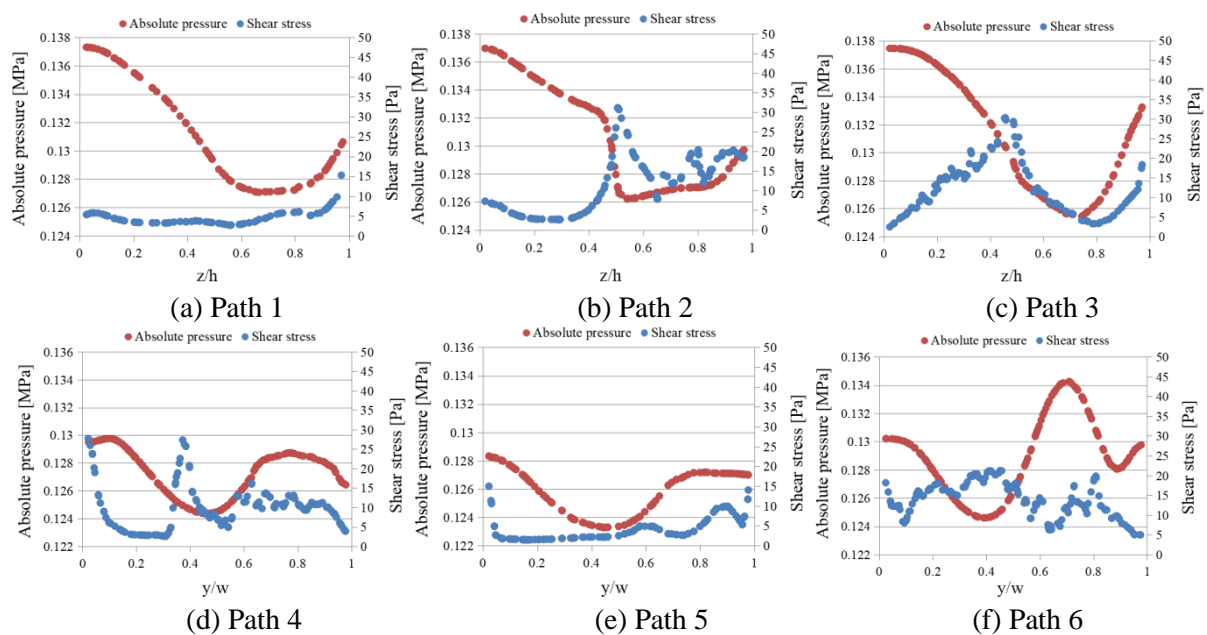


Figure 6. Absolute pressure and shear stress distribution.

As shown in figure 5, in the analysis model, Path 1 and 5 are set as the center lines of the flow path, and Paths 2, 3, 4, 6 are set along the lines 0.1 mm away from the wall. Figure 6 shows the pressure distributions and the shear stress distribution along Path 1-6. The maximum shear stress appears along Path 3. The shear stress was calculated as the product of strain rate and viscosity [3]. Along Paths 1, 2, 3, the pressure decreases with increasing z/h initially and finally increases. The total pressure reduction is about 0.01 in Paths 1, 2, 3, and the maximum shear stress appears as $\tau = 30$ Pa near the corner ($z/h = 0.5$) in Path 3.

Regarding the lateral Paths 4-6, the pressure decreases with increasing y/w initially and next increases similar to the longitudinal Path 1-3, and the maximum shear stress appears near the corner. Similar results were obtained for the large apparatus. The large apparatus has larger pressure reduction but smaller maximum shear stress. The pressure reduction and the shear stress in figure 6(c) are indicated table 4.

Table 4. Analytical condition and results along the Path 3.

	Item	Large apparatus	Small apparatus	
Analysis condition	Inlet absolute pressure [MPa]	0.45	0.16	0.45
Analysis results	Average velocity [m/s]	0.71	0.40	0.95
	Decrease in pressure [MPa]	0.03	0.01	0.07
	Shear stress [Pa]	24	30	56

4. Results and discussion

Table 3 shows the experimental results of the large apparatus and the small apparatus. The nanobubble number density per cell per cycle after 30 minutes is calculated from the nanobubble number density, the number of cycles and the number of cells. In table 3, the nanobubble number density after 30 min in the small apparatus is 2.5 times larger than the one in the large apparatus. The nanobubble number density per cell per cycle in the small apparatus is 2.4 times larger than the one in the large apparatus. Table 4 shows the CFD results for both apparatuses along the Path 3. The small apparatus has smaller average velocity and smaller pressure reduction but larger maximum shear stress.

According to the experimental results, the nanobubble generation ability of the small apparatus is 2.4 times larger than that of the large apparatus, and the CFD analysis shows that the shear stress is 1.3 times (2.3 times if the inlet pressure is set to the same value to the large apparatus) larger than that of the large apparatus, which means that the experimental results were confirmed by the CFD analysis. These results show that the shear stress is greatly related to the nanobubble generation ability, and the nanobubble generation ability is better in the small apparatus.

5. Conclusions

In this study, the experiment study was conducted for both large and small apparatuses of honeycomb structural generator with the nitrogen-water mixture. Comparing the experiment with the CFD analysis, the conclusions can be summarized as follows.

- The experiment showed that the nanobubble number density after 30 minutes in the small apparatus is larger than the one in the large apparatus. In addition, the nanobubble number density per cell per cycle in the small apparatus is 2.4 times larger than the one in the large apparatus. Those results indicated the nanobubble generation efficiency is better in the small apparatus.
- The CFD analysis showed that the small apparatus has smaller average velocity and smaller pressure reduction but larger maximum shear stress compared to the large apparatus. It may be concluded that the shear stress has a great effect on the nanobubble generation efficiency.

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