Performance improvement of underwater jet pump by optimal arrangement of primary jet stream

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Abstract
In recent years, as a new application technology of jet pumps, attention is paid to a method of installing a jet pump at the bottom of a contaminated lake or a river to remove pollutants and promote purification. The large flow rate that can be generated by the jet pump supplies dissolved oxygen in the water to the stagnant area. As a result, underwater bacteria are activated, and contaminants are decomposed and removed by the activated bacteria. In this research, we aimed to pursue the structure and operating characteristics of a jet pump that consumes less power and can generate jet flow with larger flow rate. The jet pump used in this experiment consists of one or more primary nozzles and a secondary nozzle for flow amplification and is installed at the bottom of a large tank. By measuring the flow velocity distribution blown out from the secondary nozzle, the flow rate flowing out from the secondary nozzle is obtained, and the flow rate amplification factor which is the ratio with the injection flow rate of the primary nozzle can be calculated. In this research, the performance difference between a system consisting of one primary nozzle and a system consisting of two or more primary nozzles was experimentally investigated. As a result, knowledge on the optimum supply system of the primary jet was obtained.

Keywords : Underwater jet pump, Water purification, Flow amplification factor, Consumption power, Multi-injection primary jet

1. Introduction

In the past, various studies on the performance and efficiency of jet pumps have been conducted, but in many cases these studies have been carried out with jet pumps incorporated as several mechanical systems (Narui and Inagaki, 1991, Hammoud, 2006, Neto, 2011, Pandhare and Pitale, 2017). However, there are very few studies aimed at stirring a space filled with a large amount of water by an underwater jet pump (Kurokawa and Kodani, 2015, Suzuki et al., 2016).

As shown in Fig. 1, by installing a jet pump at the contaminated bottom part of a river or lake and stirring the water with a jet flow of a large flow rate, mixing of oxygen in water is promoted, and pollutants are decomposed and removed by the activated bacteria. In this study, we have pursued the structure and operating characteristics of a jet pump capable of generating the jet flow with lower power consumption and larger flow rate. The experimental jet pump was installed in a large tank and the velocity distribution of the jet stream under various operating conditions was measured.

The emitted flow rate from the secondary nozzle can be calculated from the measurement result of the velocity distribution, and the flow rate amplification factor which is the ratio with the jet flow rate of the primary nozzle can be obtained. Since this flow rate amplification factor is an important index showing the operation efficiency of the jet pump, it is possible to study the optimization of the structure of the jet pump by examining the change in this value.
2. One-dimensional basic theory of jet pump

Using one-dimensional primitive equations, the operating characteristic of a jet pump can be analyzed (Sabersky et al., 1971, Nakayama, 1998). Using the analytical model shown in Fig. 2, the following equations are obtained.

\[
\left[ \text{Momentum of fluid flowing out of inspection volume during unit time} \right] = \frac{\pi D^2}{4} \rho V_2^2
\]

(1)
"The conservation law of momentum" of one-dimensional hydrodynamics can be written as follows using above mentioned Equations from (1) to (3).

\[ (3) = (1) \quad \text{–} \quad (2) \]  

Using this relation and the following continuity equation of the flow that flows into and out of the inspection volume,

\[
\frac{\pi}{4} (D^2 - d^2) V_1 + \frac{\pi}{4} d^2 V_0 = \frac{\pi}{4} D^2 \rho \]

namely, we obtain the following relation about the one-dimensional model of jet pump.

\[
P_2 - P_1 = \rho \frac{d^2}{D^2} \frac{D^2 - d^2}{D^2} (V_0 - V_1)^2
\]

This formula shows that \( P_2 - P_1 \) is always a positive value. That is, it indicates that the jet pump sends out water against the downstream pressure \( P_2 \) higher than the upstream pressure \( P_1 \) and is operating as a pump. Further, Eq. (6) shows that the pressure difference increases in proportion to the square of the flow velocity difference \( V_0 - V_1 \) (this means the discharge flow rate increases as the flow velocity difference increases), and \( d/D \), i.e., the aperture ratio between the primary nozzle and the secondary nozzle is an important parameter affecting the performance.
3. Experimental setup and data analysis method
3.1 Experimental setup

Figure 3 shows the schematic diagram of the large tank (1800 mm × 900 mm × 900 mm in depth) used in this study. The primary nozzle made of stainless steel has a length of 100 mm, an outer diameter of 10 mm and an inner diameter of 6 mm. The secondary nozzle made from PVC has an inner diameter of 30 mm to 78 mm and a length of 225 mm. Moreover, the relative position $\Delta X$ between the primary nozzle and the secondary nozzle is adjustable (when the value of $\Delta X$ is negative, the primary nozzle is outside the secondary nozzle). Further, the water in the tank is supplied to the primary nozzle with a centrifugal pump (maximum pressure head : 23 m, rated output : 0.4 kW). The rotational speed of the three-phase AC motor which drives the pump can be controlled by an inverter (output frequency : 0 to 60 Hz) and the discharge flow rate can be adjusted arbitrarily.

The velocity distribution of the jet stream emitted from the secondary nozzle was measured using a total pressure probe. This is fixed to the 3 axis drive stage, and the position of this probe can be set precisely.

Figure 4 shows the structure of the jet pump used in this experiment. Figure 4(a) shows a conventional type with which the primary nozzle consists of one central nozzle. Figure 4(b) shows a variation type with which the primary nozzle consists of four side injection nozzles installed in the side wall of the secondary nozzle and one central nozzle.

Figure 5 shows the pipe line arrangement for multi-nozzle injection. The flow rate $q$ supplied from the pump is distributed to $q_1$ sent to the central primary nozzle and $q_2$ sent to the four side nozzles.

Figure 6 shows the photographs of the tank experimental device used in this research.
Fig. 4  Structure of the jet pump used for this experiment. (a) Conventional type with one primary nozzle. (b) Variation type with four side injection nozzles added as primary nozzles.

Fig. 5  Pipe line arrangement for multi-nozzle injection.
3.2 Data analysis method

The flow velocity was measured by moving the total pressure probe to a measurement point obtained by dividing the nozzle diameter at equal intervals on the surface 2 mm downstream from the outlet of the secondary nozzle. The measurement points of the flow velocity are shown in Fig. 7. The total number of the velocity measurement points used for flow rate calculation is 37.

If Bernoulli's theorem is applied with the total pressure value measured at each point as $P_0$, the water depth at the probe position as $h$, the water density as $\rho$, and the gravitational acceleration as $g$, the flow velocity $V$ is expressed by the following equation.

$$V = \sqrt{\frac{2(P_0 - \rho gh)}{\rho}}$$  \hspace{1cm} (7)

Furthermore, the flow rate $Q$ discharged from the secondary nozzle is denoted by the product of the average flow velocity $V_{av}$ in the nozzle exit surface and the nozzle cross-sectional area $A$. Namely,

$$Q = A \cdot V_{av} = A \cdot \left\{ \frac{(V_1 + V_2 + \cdots + V_{37})}{37} \right\}$$  \hspace{1cm} (8)
Moreover, if the jet flow rate of a primary nozzle is set to $q$, the flow amplification factor $\eta$ is defined as follows.

$$\eta = \frac{Q}{q}$$  \hfill (9)

4. Results and Discussion

4.1 Influence of secondary nozzle diameter on jet pump performance

A performance characteristic of a jet pump based on the one-dimensional theory of fluid dynamics is represented by the Eq. (6). This result suggests that the aperture ratio $d/D$ between the primary nozzle and the secondary nozzle is an important parameter affecting performance.

Figure 8 shows the results of measurement of the velocity distribution of the jet flow emitted from the secondary nozzle on the horizontal central axis 2 mm downstream from the outlet surface, using the normal type jet pump shown in FIG. 4 (a). The two cases where the secondary nozzle diameter is 30 mm and 78 mm are shown. The supply flow rate to the primary nozzle is 24 L/min in both cases. The velocity value at each measurement point is calculated by the Eq. (7) using the total pressure value measured by the probe. When the nozzle diameter is 30 mm, the velocity gradient between the central part of the jet and the part near the wall surface is large, but when the nozzle diameter is 78 mm, the velocity gradient is gentle.

The amplified flow rate discharged from the secondary nozzle is calculated by the Eq. (8) using the average flow

![Fig. 8 Velocity distribution of the jet discharged from the secondary nozzle.](image)

![Fig. 9 Influence of the secondary nozzle diameter on the amplified flow rate.](image)
Table 1  Experimental conditions.

| Primary nozzle arrangement | Diameter of secondary nozzle [mm] | Preset value of inverter output frequency [Hz] | Flow distribution between nozzles [%] |
|----------------------------|-----------------------------------|-----------------------------------------------|-------------------------------------|
| Single-nozzle injection    | 30, 45, 60, 78                    | 30, 45, 60                                    | $q_1 = 100$                         |
| Multi-nozzle injection     | 78                                | 30, 45, 60                                    | $q_1 : q_2 = 60 : 40$               |
| Multi-nozzle injection (side injection only) | 78                                | 30, 45, 60                                    | $q_1 : q_2 = 30 : 70$               |

velocity measured at the 37 measurement points. Figure 9 shows the measurement result of the amplified flow rate when the diameter of the secondary nozzle is varied using the conventional type jet pump shown in Fig. 4 (a) under the condition that the flow rate of the primary jet is constant at 24 L/min. It can be seen from the figure that the amplified flow rate tends to increase as the secondary nozzle diameter increases. Further, the experimental conditions carried out in this research are summarized in Table 1.

4.2 Effect of primary nozzle arrangement on jet pump performance

In order to investigate the influence of the primary nozzle arrangement on the performance of the jet pump, performance evaluation was carried out under various operating conditions using a secondary nozzle having an inner diameter of 78 mm which generates the maximum flow rate. This experiment was conducted on the two types of primary jet supply systems shown in Figs. 4 (a) and (b).

Figure 10 (a) shows the measurement results of the amplified flow rate emitted from the secondary nozzle and the amplification factor, using the conventional jet pump shown in Fig. 4 (a). In this figure, it can be seen that the amplified flow rate increases as the primary jet flow rate increases. On the other hand, the amplification factor shows a downward tendency as the primary jet flow rate increases. This is considered to be caused by an increase in energy loss related to pressure loss occurring in the secondary nozzle due to an increase in the amplified flow rate.

(a) Amplified flow rate and amplification factor.
(b) Influence of the relative position between the two nozzles on amplification factor.

Fig. 10  Performance of the conventional jet pump with single injection nozzle shown in Fig.4(a).
(a) Amplified flow rate and amplification factor.
(b) Influence of the relative position between the two nozzles on amplification factor.
Figure 10 (b) shows the influence of the relative positions of the primary nozzle and the secondary nozzle on the amplification factor. When the gap between the primary nozzle and the secondary nozzle is 20 mm (ΔX = -20 mm), the highest amplification factor is shown under all experimental conditions although it is a slight amount of value.

Figure 11 (a) and (b) show the measurement results of the amplified flow rate and amplification factor as a function of the velocity of the primary jet in each primary nozzle arrangement. Regarding the amplified flow rate, it can be seen that the multi-nozzle injection system generates a large flow rate even at a low flow velocity. On the other hand, regarding the flow amplification factor, the single-nozzle injection method shows the highest amplification factor. In the low flow velocity region, the multi-nozzle injection method using only the side nozzles shows a high amplification factor. In the figure, in the multi-nozzle injection using both the center nozzle and the side nozzles, the flow velocity of the side nozzle is different from the flow velocity of the center nozzle, and therefore the average flow velocity of the both is plotted.

Figure 12 (a) and (b) show the amplified flow rate and flow amplification factor as a function of the flow rate of the primary jet. The flow rate range of the primary jet differs under each experimental condition based on the difference in pressure loss occurring in the pipeline from the supply pump to the primary nozzle outlet. From this figure, the side injection system produces the maximum amplified flow rate in the low flow rate region of the primary jet. This injection system suggests that a large amplified flow rate can be obtained even in a large flow rate range by reducing the pressure loss.
By keeping the flow rate of the primary jet constant, we examined which experimental condition gives the maximum amplified flow rate. A value of 18 L/min was chosen as a feasible supply flow rate under all experimental conditions. The experimental results are shown in Fig. 13. It can be seen that the multi-nozzle type jet pump can achieve a more amplified flow rate than the conventional type with single primary nozzle. Under the multi-nozzle type experimental conditions, the condition using only side injection shows the highest performance. Moreover, it was found that the flow distribution ratio \( q_2/q_1 \) between the center nozzle and the side nozzles influences the performance. In this case, it is considered important to satisfy the condition indicated by \( q_2 > q_1 \) for flow rate amplification.

The former discussion is based on the supply flow rate, but the measurement result based on the consumption power of the drive pump is shown in Fig. 14. In this case, the set output frequency of the inverter is 30, 45 and 60 Hz under all experimental conditions as in the previous experiments. Obviously, a multi-nozzle system with a large supply flow rate achieves a more amplified flow rate. However, since the relation between the power consumption of the pump and the discharge flow rate strongly depends on the pressure loss of the pipeline connecting the pump and the primary nozzle, by reducing the pressure loss of the pipeline under each experimental condition further increase in flow rate is expected.

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**Fig. 13** Comparison of the amplified flow rate which each nozzle arrangement generates under the condition of an equal primary flow rate.

**Fig. 14** Correlation between the consumption power of the supply pump and the amplified flow rate in each nozzle arrangement.

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\[ q = 18 \text{ (L/min)} \]

\[ q_1 : q_2 = 60 : 40 \]

\[ q_1 : q_2 = 30 : 70 \]

\[ q_1 : q_2 = 0 : 100 \]
5. Conclusions

As a part of research on effective diffusion of water by an underwater jet pump aiming at water purification in contaminated areas of rivers and lakes, performance evaluation of a small underwater jet pump using a large water tank was conducted. In this research, the influence of the difference in the supply system of the primary jet on the amplified flow rate was experimentally investigated. The conclusions obtained in this study are shown below.

1. The amplified flow rate of the jet pump tends to increase as the diameter of the secondary nozzle increases.
2. The amplified flow rate of the jet pump increases in proportion almost to the flow rate of the primary jet. On the other hand, the flow amplification factor shows a tendency to decrease as the primary flow rate increases. This is considered to be due to an increase in pressure loss occurring in the secondary nozzle as the amplified flow rate increases.
3. The effect of the flow velocity of the primary jet on the amplified flow rate is greater in the multi-nozzle system than in the conventional type. On the other hand, the effect on the flow amplification factor is the most excellent in the conventional type.
4. When the primary flow rate is constant, the multi-nozzle system can generate more amplified flow rate than the conventional system. In particular, the multi-nozzle system using only the side injection nozzles achieved the maximum amplification efficiency.
5. As for the amplified flow rate based on the power consumption of the supply pump, the multi-injection system which can generate the maximum primary flow rate under constant power consumption is the most excellent.

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