Experiment and Performance Prediction of Bubble-Jet Type Air-Lift Pump for Dredging Sediments on Sea and Lake Beads

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Abstract: Sadatomi invented a bubble-jet-type air-lift pump for dredging sediments deposited on sea and lake beds by striking water jet with air bubbles. In our previous study [6], experiments were conducted using 50 mm I.D. and 5.0 m long pipe as the upriser of the pump, three kinds of spherical particles of different size and density as the test particle, and 3.0 wt % saltwater as the test liquid. In addition, the submergence ratio, the ratio of the upriser length submerged in water to the total length, was changed from 0.76 to 0.84. Furthermore, Yoshinaga et al.'s model for predicting pump performance was modified and validated by the experimental data reported so far by the authors. In the present paper, new simulation results for designing larger system is described together with a summary of the previous study [6].

Key-Words: Air-lift pump, Dredging, Sediment, Seabed, Bubble-jet, Performance, Experiment, Prediction

1 Introduction

In fisheries in inland seas, uneaten feed and droppings deposit on the sea beds, and in lakes and city water reservoirs, fallen leafs, mud and sand also deposit on their beds. The deposits cause the shortage of oxygen in water as well as the water capacity in lakes and city water reservoirs. In order to remove such deposits, an air-lift-pump has been paid attention because of a merit of rarely occlusion in comparison with conventional pumps. However, a common air-lift pump shown in the left of Fig. 1 cannot remove the deposits compressed because air alone is injected into the upriser. In order to overcome the deficit, Sadatomi invented a unique air-lift-pump called bubble-jet-type air-lift-pump (BJT pump for short) [1] shown in the right of Fig. 1.

In the BJT pump, two or more bubble-jet (BJ) generators are equipped beneath the skirt of the pump in order to attack the sediments by water jets with air bubbles. By the attack, the sediments are broken into small parts and floated, thus the sediments together with water and air can be pump up, and finally conveyed to elsewhere [1, 2]. The BJT pump seems useful also for the promotion of chemical and bio-chemical reactions in reservoirs.

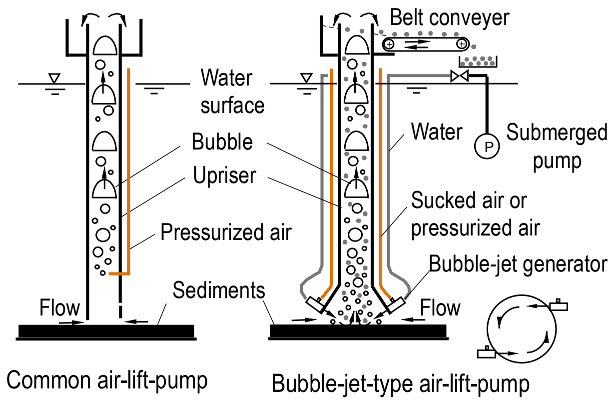

Fig. 1 Common and bubble-jet-type air-lift pumps

In our previous studies [2-6], experiments were conducted for two kinds of systems, (a) an original system [2] applicable to shallow water zone and (b) a revised system [3-6] applicable to deep water zone up to 50 m where most fisheries exist. In the original system, if pressurized water is supplied to the BJ generator, air is automatically sucked by a vacuum pressure behind the sphere inside the BJ generator. In the revised system, the water supply rate is restricted to a value in which air is not automatically sucked, but pressurized air is supplied to the BJ generator. In the analysis, Yoshinaga et al.'s model [7] for predicting pump performance was modified [6] in order to remove its weak point.

In the present paper, new simulation results for designing larger system, applicable to deep water zone up to 50 m, are described together with a summary of the previous study [6].

2 Experiment [6]

2.1 Experimental apparatus

Figure 2 shows the apparatus with a 50 mm I.D. and 5.0 m long transparent acrylic pipe as the upriser. One of the test particles, listed in Table 1, was put into a lower tank as sediment, and 3.0 wt % artificial saltwater was poured into the tank, upriser and return pipe. The density of the saltwater at 20 °C was 1.019 kg/m^3 (2% higher than water), the viscosity 1.045 $\times$ 10^{-3} Pa· s (6.6 % higher) and the surface tension 0.066 N/m (10 % lower). In order to know the effects of the submergence ratio, $\sigma = H_S/H$, on the pump performance, H_S was changed from 0.76 H to 0.84 H. After that, the water was pumped from the bottom of the lower tank to the BJ generators, while air was supplied to it with a compressor, i.e., the revised system was adopted. The inlet flow rates of water and air to the BJ generators were measured with turbine flow meter and rotameter, respectively. The water jet with air bubble from the BJ generators attacked the particles bed, and a part of the particles beneath the skirt were floated and sucked into the upriser with water and air bubbles. They flowed through the upriser and entered into the separator tank. The air was released to atmosphere, while the particles and the water were separated with a net. The flow rate of the particles was measured with a beaker and a stopwatch while that for the water with an electromagnetic flow meter, respectively within the accuracy of 2 %. After the measurements, the particles and the water were returned to the lower tank via the return pipe.

Table 1 Specifications of particles [5, 6]

Name	Materials	Density kg/m^3	Particle mean dia. d_S mm	Free fall velocity in water $u_{S\infty}$ m/s		Re_s **
				Water	3.0 wt % saltwater	Water
Sa-07*	Sand	2556	0.72	0.06	-	44.4
Gla-20	Glass	2738	1.94	0.28	0.27	534
Cer-10	Ceramics	3761	1.21	0.25	0.25	306
Cer-20	Ceramics	3703	2.12	0.38	0.37	804

* The test liquid was water alone [5].

** Re_s is defined as $\rho_L u_{S\infty} d_S/\mu_L$.

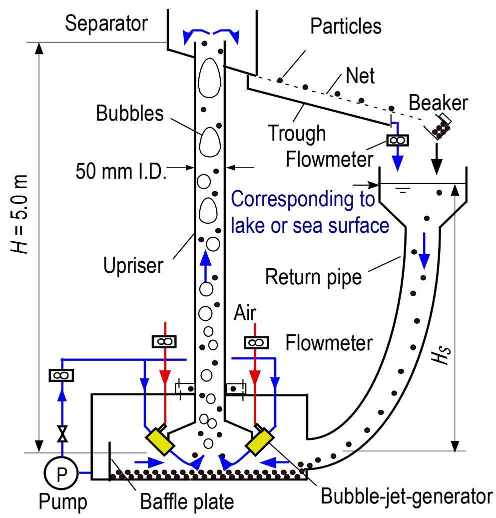

Fig. 2 Experimental apparatus

The air discharge rate at volume from the upriser, Q_{GO}, was determined from the measured inlet mass flow rate by subtracting air leak rate from the upriser skirt to the outside in the lower tank. The accuracy of Q_{GO} so determined was within 3 %. When the velocity of water jet with bubbles from the BJ generator was high, some sediment beneath the upriser skirt was pushed outside, leading to a reduction in water and particles discharge rates. In order to prevent the reduction, water supply rate at volume to each BJ generator was limited to Q_{LI} = 17.5 to 18.0 l/min, in which air was not automatically sucked but the particles were well floated. At the fixed water supply rate, air supply rate to the BJ generator was systematically changed to study the pump performance.

In addition, the total hydraulic power consumed by the BJT pump, L_T, was determined as $L_T = L_L + L_G$ [8], where the water power, L_L, and the pneumatic power, L_G, were calculated by substituting the measured pressures of water and air at the inlet of BJ generator, P_{LI} and P_{GI}, the supplied rates of water and air, Q_{LI} and Q_{GI}, and the mean velocities, u_{LI} and u_{GI}, into the following equations:

$$L_L = \left(P_{LI} + \rho_L u_{LI}^2 / 2\right) Q_{LI} \,, \tag{1}$$

$$L_G = \left(P_{GI} + \rho_G u_{GI}^2 / 2\right) Q_{GI} \,. \tag{2}$$

Here, ρ_L and ρ_G are the densities of water and air at the inlet of BJ generator.

2.2 Bubble jet generator

Figure 3 shows the BJ generator. Water is supplied from the right end, while air is supplied from many small holes drilled on the pipe just downstream from the sphere. The air supplied is cut off into a number of small bubbles by high shear water flow. The diameters of the pipe and the sphere were 11.0 mm and 9.53 mm similarly to a micro-bubble generator [9], while that of small holes were 1.0 mm, being different from that of the micro-bubble generator. Four BJ generators were equipped below the skirt, as seen in Photo 1. We can see the inlet of the upriser in the centre of the 41.5 cm O.D. skirt. The pitch diameter of the four BJ generators was L = 25 cm, which was confirmed to be the best dimension in a preliminarily test.

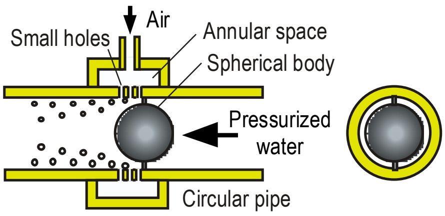

Fig. 3 Bubble-jet-generator

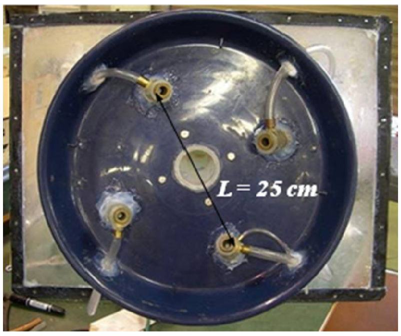

Photo 1 Four bubble-jet-generators and the inlet of 50 mm I.D. upriser seen underneath the skirt

3 Prediction of Pump Performance [6]

Yoshinaga et al. [7] proposed a performance prediction model of airlift pump for lifting particles. The model, however, can predict water discharge rate alone by giving air supply rate and particle discharge rate as input data. So, in order to predict both water and particles discharge rates at volume by giving air supply rate alone as input data, a new correlation of the particles flow rate fraction in particles-water mixture, β_S (= Q_{SO} / (Q_{SO} + Q_{LO})), was developed [5, 6] by accounting for that the most particles exist in water in the upriser.

For spherical particles in water system with the upriser of 26 mm and 50 mm I.D. [5], we obtained:

$$\beta_S = 407 \cdot \left(\frac{d_S}{D}\right)^{-0.16} \left(\frac{\rho_S}{\rho_L}\right)^{-3.4} \left(\frac{\rho_L u_{S\infty} d_S}{\mu_L}\right)^{-1.0} \quad (3)$$

Here, d_S/D is the particle to upriser diameter ratio, ρ_S/ρ_L the specific gravity of particle, and $\rho_L u_{S\infty} d_S/\mu_L$ the particle Reynolds number. Eq. (3), however, could not predict sand data. In [6], thus Eq. (3) was slightly changed as:

$$\beta_S = K \cdot \left(\frac{d_S}{D}\right)^{-0.16} \left(\frac{\rho_S}{\rho_L}\right)^{-3.4} \left(\frac{\rho_L u_{S\infty} d_S}{\mu_L}\right)^{-1.0} \quad (4)$$

Here, K = 407 for spherical particles, while K = 20 for the sand in our previous study. Figure 4 shows a comparison of particles flow rate fraction between calculation by Eq. (4) and experiment [5, 6]. The experimental data are the mean values in each efficient operation condition. All data including sand data marked as star symbol agree quite well with calculation by Eq. (4), irrespective of the particle specifications, the salinity, and the upriser diameter. However, the applicability of K = 20 to other non-spherical particles, such as larger sand and gravels, must be studied in future.

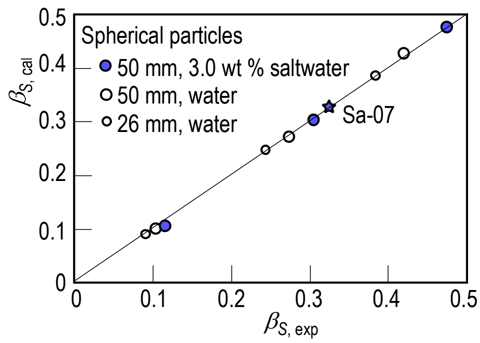

Fig. 4 Comparison of particles flow rate fraction between calculation by Eq. (4) and experiment in efficient operation condition

By incorporating Eq. (4) into Yoshinaga et al.'s model [7], we could predict both particles and water discharge rates by giving air supply rate alone as input data. The basic equation of the modified model is the following momentum equation:

$$\Delta(\rho_G j_G u_G + \rho_L j_L u_L + \rho_S j_S u_S)_{in-out} - dP_E - \frac{4}{D}\int_E^O \tau_3 dz$$
$$- \int_E^O (\rho_G \alpha_G + \rho_L \alpha_L + \rho_S \alpha_S) g dz + \rho_L g H_S = 0 \quad (5)$$

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Here, the first term is the change in momentum of three phases from the inlet to the exit of the upriser, the second to the fourth terms the inlet, the wall and the hydrostatic pressure losses, and the fifth term the hydrostatic pressure exerted at the upriser inlet from the outside. These terms are calculated by the same equations as those used by Yoshinaga et al. [7] except for the second term. The second term is calculated by accounting for the effects of air, water and particle flows as:

$$dP_E = \zeta(\rho_G\alpha_G + \rho_L\alpha_L + \rho_S\alpha_S)(j_G + j_L + j_S)^2 / 2 \quad (6)$$

Here, ζ, the inlet pressure loss coefficient.

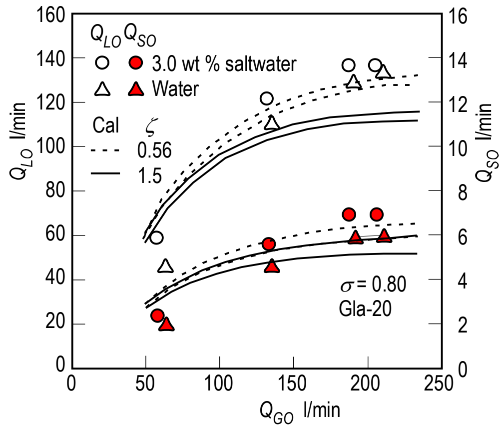
Figures 5 (a)-(d) compare the discharge rates of water and particles between the calculations by the above modified model and the experiments. The left and the right ordinates are the discharge rates of water and particles, Q_{LO} and Q_{SO}, while the abscissa is the discharge rate of air, Q_{GO}. The calculated value with the inlet loss coefficient of ζ = 0.56 (applicable to single-phase turbulent flow in a pipe with right-angle inlet) is drawn as broken curve, and that with ζ = 1.5 as solid curve in order to study its sensitivity in calculation.

In Figs. 5 (a), (b), the data for 3.0 wt % saltwater system and water system are plotted as circular and triangular symbols, and Q_{LO} and Q_{SO} data as open and darkened symbols. Both Q_{LO} and Q_{SO} increase with Q_{GO}, because the density difference between the inside and the outside of the upriser, i.e. the driving force of the pump, increases with Q_{GO} in the present experimental range. Furthermore, Q_{LO} and Q_{SO} are 5 to 30 % higher in the saltwater system than the water system. The experimental data at the efficient operation condition of around Q_{GO} = 200 l/min are well predicted by the calculations for Gla-20 with ζ = 0.56 and for Cer-20 with ζ = 1.5. In addition, the prediction on the salinity effects is qualitatively predicted in Fig. 5 (a).

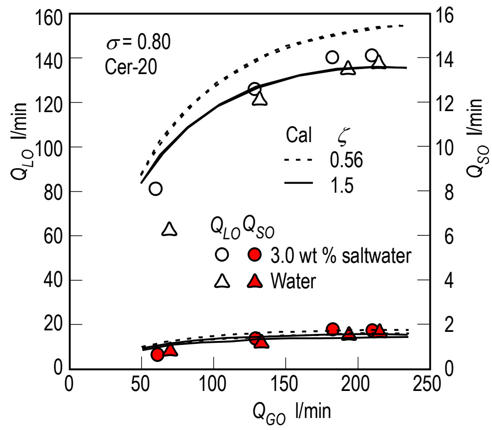
In Fig.5 (c), the data for different spherical particles for saltwater system at σ = 0.84 are well predicted by the calculations with ζ = 0.56. In addition, predicted value of Q_{LO} is almost independent of particles specifications similarly to the experimental data.

In Fig. 5 (d), the data for Gla-20 at σ = 0.84 are well predicted by the calculations with ζ = 0.56 at the efficient operation condition, while those at σ = 0.76 are about 10 % higher than calculations.

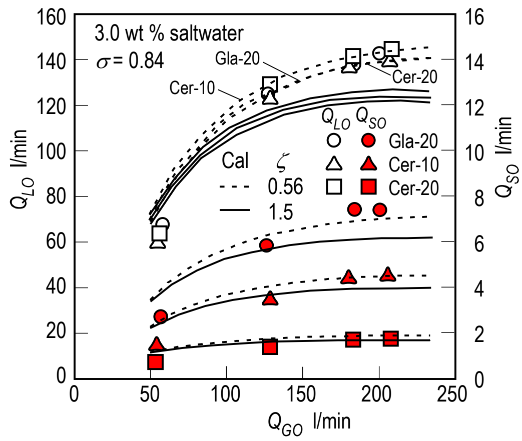
Figure 6 compares the 0.72 mm diameter sand data for water system in 26 mm I.D. upriser [5] with calculations. The data at σ = 0.76 and 0.80 are about 20 % higher than the calculations at the efficient operation condition. However, since the discharge rate data for such a small sand system had 10 % or more error because of difficulty in measurement, the above prediction error seems within a tolerance.



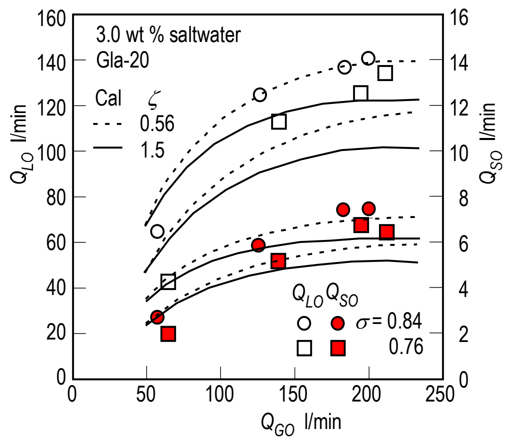
(a) Effects of salinity (Gla-20)



(b) Effects of salinity (Cer-20)



(c) Effects of particles specifications



(d) Effects of submergence ratio

Fig. 5 Comparison of discharge rates between experiment for spherical particles and calculation

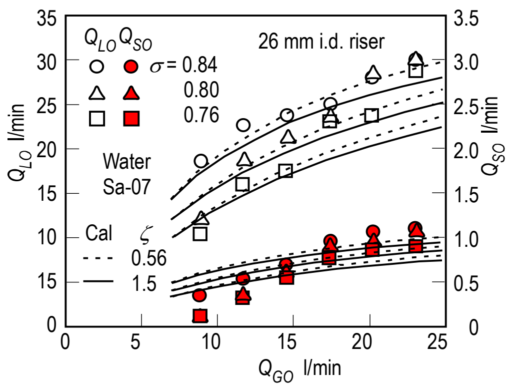


Fig. 6 Comparison of discharge rates between experiment for sand and calculation

From the comparisons in Figs. 5 (a)-(d) and 6, we can conclude that the modified model [6] is useful for predicting discharge rates of water and particles, regardless of the difference in salinity in water, particles specifications, submergence ratio and upriser diameter. In addition, as the inlet loss coefficient, ζ = 1.5 is recommended because the particle discharge rate is underestimate, i.e., safety side in designing.

4 Simulation of Larger System

The modified model mentioned above is useful for predicting the performance of the BJT air-lift pump in practical use. So, we tried to predict the performance under the following conditions: The height of the upriser, H, is 50 m for simulating larger system in fisheries etc.; the submergence ratio, σ, is 0.98, i.e., 1.0 m in super-aqueous height; the diameter of the upriser, D, is 50 to 300 mm; the water is 3 wt % saltwater; the sediments deposited is the sand used in our previous study [5]; the total of water supply rate to the four BJ generators is increased depending on D from 71 l/min, being the same as that in our previous study for 50 mm upriser [5]. In addition the inlet loss coefficient, ζ, is 1.5, being safety side in designing.

Figure 7 shows a predicted result on the particle discharge rate, Q_{SO}, against the air supply rate, Q_{GO}, under the prescribed condition. Tangential lines to the respective calculated curves through the origin are drawn to find the optimum operation condition for the respective upriser diameters. Q_{SO} at the optimum condition is roughly proportional to Q_{GO}, irrespective of the upriser diameter. Thus, if someone wants to remove the sediment, say, at 0.4 m^3/min, he or she has better to choose 300 mm in upriser diameter and 8.0 m^3/min in air supply rate.

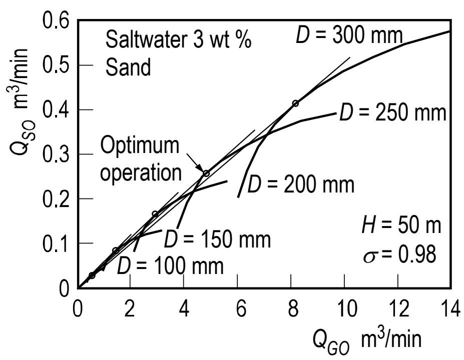


Fig.7 Predicted particle discharge rate against air supply rate for larger systems of different upriser diameter at the prescribed condition

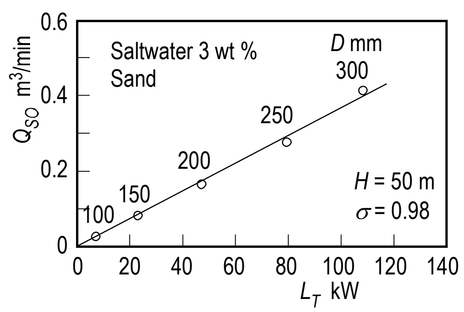


Fig. 8 Predicted particle discharge rate against total power at the optimum operation condition for different upriser diameter

Figure 8 shows a predicted result on the particle discharge rate, Q_{SO}, against the total power, L_T, at the optimum operation condition. Here, L_T is the sum of the water power, L_L, and the pneumatic power, L_G, calculated by Eq. (1) and Eq. (2). Of

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these powers, L_L is 0.70 to 4.20 kW depending on the upriser diameter in the present prediction. Thus, except for at D smaller than 100 mm, L_G is the major part of L_T and L_T value shown in Fig. 8 is helpful to select an optimum compressor for supplying air to the BJ generator.

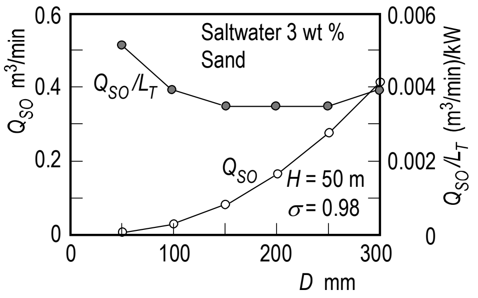

Fig. 9 Predicted particle discharge rate and particle discharge rate to total power ratio against upriser diameter at the optimum operation condition

From an economical point of view, the ratio of the particle discharge rate to the total power, Q_{SO}/L_T, is higher the better. Fig. 9 shows a result of such an examination. Q_{SO} increases with D as was seen in Figs. 7 and 8. On the other side, Q_{SO}/L_T is higher in D = 50 mm and 100 mm than D > 150 mm. However, the use of larger system of D > 150 mm is more economical than the multiple use of smaller system of D = 50 mm and 100 mm when Q_{SO} is larger than about 0.1 m^3/min because the total cost of equipments becomes small.

5 Conclusion

Regarding the bubble-jet-type air-lift pump invented by Sadatomi, a new simulation results for designing larger system, applicable to deep water zone up to 50 m, are studied. In addition, the BJT air-lift pump itself, the hydraulic performance and the performance prediction model in the present state are explained by referring [6]. The findings of the simulation are:

(1) The particle discharge rate, Q_{SO}, at the optimum operation condition is roughly proportional to Q_{GO}, irrespective of the upriser diameter.

(2) L_T value shown in Fig. 8 is helpful to select an optimum compressor for supplying air to the BJ generator.

(3) The use of larger system of D > 150 mm is more economical than the multiple use of smaller system of D < 100 mm when Q_{SO} > 0.1 m^3/min.

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