Study on Development of Ejector of Bubble Jet Engine (BJE) -Measurement of Thrust -

B Ono, K Nakashima, T Shigematsu and K Morishita

1) Sasebo National College of Technology 1-1, Okishin-cho, Sasebo City, Nagasaki Pref., 857-1193 JAPAN
ono@post.cc.sasebo.ac.jp

Abstract. The AUV (Autonomous Underwater Vehicle), which is used for the present seabed investigations, has obtained the thrust with the screw driven by the battery. However, it has a disadvantage because of its size and cost. Therefore, this research is carried out to propose the Bubble Jet Engine (BJE) as an alternative propulsion device. It can directly transform combustion energy into kinetic energy, so it is expected that BJE can also rise the level of propulsion efficiency. This research aims at measuring exhaled mass flow rate and thrust to design ejectors, which become the core of BJE, and exploring practical possibility of BJE. Vertical type gas-water ejector experimental apparatus for measuring water entrainment was employed in order to understand the characteristics of operation conditions, such as inlet distance, air pressure of nozzle, diameter of nozzle, and so on. In addition, experiments for measuring the thrust in the condition of ejector were executed with horizontal type apparatus in water. However, the influence of the ejector to improve thrust can't have been recognized with high-pressure air at room temperature yet.

1. INTRODUCTION

The idea of using high-pressure gas as a driving force has been proposed by Witte (1969) and Mottard et al. (1961) since the old days. However, there has been no report in which the idea is applied to the practical use.

On the other hand, water jet promotion obtains the thrust by spouting the water, which is pumped up from a bottom of ship or from a rear nozzle, directly with high-pressure pump or screw. Recently, it has actually been used widely, such as the water motorcycle, the high-speed patrol boat, the passenger ship and so on. It is conceivable that the range of its application will spread out more if high-pressure gas can be used instead of the high-pressure pump and the screw. However, it is still difficult to transmit kinetic energy of the high-speed gas to water efficiently. Tsutahara et al. (2000) has actively been working on the research of the nozzle for the ship with high-speed gas used. It is also reported that efficiency is raised when steam is used instead of the high-pressure gas(Tsutahara et al., 2004). Thereupon, BJE aims at the high increase in its efficiency by transforming energy of the high temperature gas into kinetic energy of water using the high-pressure combustion gas with an ejector.

Balamurugan et al.(2007) show the behavior inside the ejector where a liquid mixes with the gas with simulation, and they investigate pump ability of the high-pressure gas experimentally in water pumping experiment. This research examines the ejector performance in various experimental conditions empirically and aims at the commercialization of BJE.

2. Model of BJE
2.1 Structure

Ejector is the element in which gas is mixed with water, and the improvements in the propulsion efficiency can be realized by taking as much water as possible into the ejector. Figure 1 shows the schematic of BJE model. BJE is composed of fuel, a combustion vessel and an ejector. Hydrocarbon such as propane and butane is used as fuel. First, oxygen and fuel are burned in the combustion vessel. The combustion gas introduces seawater into an ejector through seawater intake. For this study, the ejector is the most important element where mixture of seawater and conversion gas form gas-liquid phase called bubble jet, and gives thrust by spouting.

![Fig. 1 Schematic of BJE model](image)

2.2 Theory of BJE

This bubble jet engine system is expected to have high efficiency to transform combustion energy into the kinetic energy directly, reducing mechanical loss. The characteristics may be classified into three advantages under the following heads; (1) Improvement of thrust; (2) Improvement of propulsive efficiency; and (3) Transformation from heart energy to kinetic energy;

The first advantage is that improvement of thrust to reduce loss diffused by attaching an ejector. The second is that the propulsive efficiency becomes predominance when the velocity of the gas spouted from nozzle is the same as the navigation speed of hull. The ejector can fully slow down the high-speed gas as bubble jet flow. The third is the possibility that thermal energy changes into the kinetic energy when the gas of $500\, ^\circ C$ or higher is mixed with water in ejector.

This paper, however, discusses just (1) the improvement of thrust. Figure 2 shows schematic of jet from the nozzle without ejector and with one. Without ejector, the high-speed combustion gas is spouted out directly into water, therefore the law of conservation momentum is:

$$\dot{m}_{g0}v_{g0} = \dot{m}_{g1}v_{g1} + \Delta L_1 \quad (1)$$

and with ejector:

$$\dot{m}_{g0}v_{g0} = \dot{m}_{j2}v_{j2} + \Delta L_2 \quad (2)$$

where $\dot{m}_g$: mass flow rate of gas[kg/s], $v_g$: velocity of gas[m/s], $\dot{w}$: mass flow rate of water[kg/s], $v_w$: velocity of water[m/s], $\dot{j}$: mass flow rate of bubble jet[kg/s], $v_j$: velocity of bubble jet[m/s],

$$\dot{m}_{j2}v_{j2} = \dot{w}_{w2}v_{w2} + \dot{j}_{g2}v_{g2} \quad (3)$$

2
The thrust of the purity net which can be taken out is \( m_{g_0}v_{g_0} \) and \( m_{j_0}v_{j_0} \), and it can be thought that the loss \( \Delta L_1 \) without the ejector grows bigger than the loss \( \Delta L_2 \) with the ejector. In other words, regarding the reduction of loss, the result is more favourable when the bubble jet hits water than when the light gas hits directly heavy water. Therefore, the possibility of improvement of thrust can be expected.

![Fig. 2 Schematic of jet](image)

3. EXPERIMENT

3.1 WATER PUMPING TEST

3.1.1 Vertical type gas-water ejector experimental apparatus

Vertical type gas-water ejector experimental apparatus, which is adopted to understand the characteristics of the ejector, is shown in Fig. 3. That is composed of a water tank (diameter: 800 mm, height: 500 mm), a nozzle and an ejector. The air compressed with a compressor instead of the combustion gas is used in this experiment. After it spouts from the nozzle and passes inside the ejector with water, it is sent to void fraction measurement part (Fig.4). The void fraction measurement pipe has two valves which open and close simultaneously.

![Fig. 3 Vertical type gas-water ejector experimental apparatus](image)
3.1.2 Experimental method and condition

The detail of the inlet of the ejector is illustrated in Fig. 5. The experimental conditions are summarized in Table 1.

To investigate the performance of the ejector, the mass flow rate and velocity of the water introduced into the ejector have to be measured. In fact, however, the measuring the mass flow rate and the velocity of water is very difficult. Therefore, the void fraction was adopted, and it enabled us to do our estimation in this experiment.

1. Estimation of mass flow rate

In this apparatus, because water to keep water level is not supplied, the mass flow rate that passes inside ejector is not steady, and it changes depending on level of water tank. However, because relation between mass flow rate and water level is linear as shown in Fig. 6, the mass flow rate at optional water level can be gained easily.

2. Estimation of velocity

Flowing water was trapped by closing the valve of void fraction measurement pipe when water level passed at the water level 450 mm(at 50 mm underneath from water surface) of the water tank, and the void fraction can derivate from space volume. Therefore the water level 450 mm is considered criterion.

Velocity of water can be written by the mass flow rate and the void fraction as next equation. That is:

\[ v_w = \frac{\dot{m}_w}{A_\phi \rho_w} \alpha \left(1 - \alpha \right) \]  

\[ \dot{m}_w : \text{mass flow rate of water[kg/s]} \quad A_\phi : \text{cross section area of flow pipe}[\text{mm}^2] \]

\[ \rho_w : \text{density of water[kg/m}^3]\]

\[ \alpha : \text{void fraction} \]

where, the influence of the gravity must be considered when water runs down in flow pipe or when it rises [Appendix 1]. However, the influence of this gravity can be ignored by positioning the void fraction measurement pipe to the same height of ejector inlet. Then, the friction loss between flow water and inside wall of the pipe is not considered at all.
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Fig. 5 Detail of the inlet of the ejector.

Table 1 Experimental condition

| Nozzle diameter d[mm] | 5, 8, 10 |
|-----------------------|---------|
| Ejector diameter Φ[mm] | 20, 40, 60 |
| Ejector Inlet distance, H[mm] | 5, 10, 20, 30 |
| Air pressure, p[MPa] | 0.3, 0.4, 0.5 |

Fig. 6 Influence of water level with mass flow rate

3.2 THRUST MEASUREMENT

3.2.1 Horizontal type thrust measurement apparatus

The schematic diagram of horizontal type thrust measurement apparatus in water is shown in the Fig. 7. This system is composed of the chamber of the cylinder type to which the high-pressure air of the compressor is being supplied, the nozzle and the ejector, and they are submerged in water. The high-pressure air, which is mixed with water in the ejector, spouted from the nozzle, and it is exhausted as a bubble jet outside the ejector. Load cell installed on the guide rail detects the thrust.
3.2.2 Experimental method and condition

Figure 8 shows the enlarged view of the ejector inlet. Experiment parameters are ① nozzle diameter $d$, ② inlet distance $H$, ③ ejector length $L$, and ④ air pressure $p$, and they are shown in table 2 as the details. The experimental method is to measure the thrust in different conditions. In this experiment, the ejector diameter $Φ$ used is only $Φ$ 60 mm, which was conducted from the result of water pumping test.

![Horizontal type thrust measurement apparatus](image)

**Fig. 7** Horizontal type thrust measurement apparatus

![Enlarged view of the ejector inlet](image)

**Fig. 8** Enlarged view of the ejector inlet

**Table 2 Experimental condition**

|   |   |   |
|---|---|---|
| ① | Nozzle $d$[mm] | 3, 4, 5, 8, 10 |
| ② | Ejector inlet distance $H$[mm] | 0, 10, 20, 30, 40, 50 |
| ③ | Ejector length $L$[mm] | 100, 200, 300, 400, 500 |
| ④ | Air pressure $p$[MPa] | 0.3, 0.4, 0.5 |
4. RESULTS AND DISCUSSION

4.1 Results of water pumping test

(1) Mass flow rate of water

The relation of mass flow rate versus inlet distance $H$ is shown in Fig. 9(d=5mm). Each data shows the average value of three experiments in the same condition. The mass flow rate increases with increasing the inlet distance below $H=20$, and doesn't almost change in the range of above $H=20$mm. There was the same trend in other nozzle diameters. It also increased according to the increase of pressure with all nozzle diameters.

(2) Void fraction $\alpha$

A change in void fraction with a nozzle diameter $d=10$mm is shown in Fig. 10. Major changes could not be observed regardless of each nozzle diameter, and it is about $0.8 \sim 0.9$. The void fraction decreased according to the increase of pressure with all nozzle diameters.

(3) I/O ratio $\eta$

The role of ejector is to give water energy, decreasing velocity of gas spouted from nozzle fully. Now, The input force $F_{in}$ that acts on the ejector and the trust $F_{out}$ of water exhausted from ejector are defined as follows:

$$F_{in} = A_d \cdot p$$  \hspace{1cm} (5)

$$F_{out} = \dot{m}_w \cdot V_w$$  \hspace{1cm} (6)

where, $A_d$; cross section area of nozzle[$mm^2$], $p$; air pressure[Pa],

Relations between $F_{in}$ and $F_{out}$ in various experimental conditions are shown in the Fig. 11. It is found that output $F_{out}$ increases with the rise of pressure in any nozzle diameter. The result plotted this output $F_{out}$ as I/O ratio $\eta = F_{out} / F_{in}$ is shown Fig. 12. The I/O ratio in a nozzle diameter 5mm is very high with every inlet distance condition. Especially, it is the highest with inlet distance 20mm at 0.5MPa in air pressure.

Thus, viewed in the above result, the high I/O ratio could be realized if the nozzle diameter 5mm in the range of this experiment condition was adopted.
Fig. 9 Mass flow rate versus inlet distance $H(d=5\text{mm})$

![Graph showing mass flow rate vs inlet distance](image)

Fig. 10 Void fraction versus inlet distance $H(d=10\text{mm})$

![Graph showing void fraction vs inlet distance](image)

Fig. 11 Relations between $F_{in}$ and $F_{out}$ in various experimental conditions

![Graph showing relations between $F_{in}$ and $F_{out}$](image)
4.2 Results of thrust measurement

(1) Without ejector

Thrust measurement in water without installing an ejector was conducted to understand nozzle performance. The thrust $F$ versus nozzle diameter $d$ in case of air pressure $p=0.5\text{MPa}$ without ejector is shown in Fig. 13. Table 3 summaries volume flow rate in each nozzle. The thrust of the nozzle of $d=5\text{mm}$ is the biggest corresponding to the volume flow rate of air. This data supports the results of water pumping test. Figure 14 shows influence of nozzle pressure on thrust. The thrust increases with increasing air pressure.
(2) **With ejector**

The relation of thrust for inlet distance H is shown in Fig. 15 (air pressure=0.5MPa, ejector diameter Φ60m). The thrust in the range of below inlet distance H=20mm increases. On the contrary, it is steady above H=20mm and for example when L=200; F=9.6N. This trend agree with the result of water pumping test; the mass flow rate of exhaust water from ejector didn’t increase in the rage of above H=20mm.

Now, Figure 15 replotted the thrust at H=30mm in Fig.16. Horizontal axis shows ejector length L. The thrust is about 9.8N below L=200, and especially at L=0, so without ejector, it is the highest 9.9N. Also it rapidly falls right down above L=200mm because of friction loss and buoyant of air in ejector. Following what has been found, it can be said that improvement of thrust regarding ejector could not be achieved.

![Fig. 13 Influence of nozzle diameter on thrust](image)

**Table.3 Volume flow rate of each nozzle**

| Nozzle diameter [mm] | 3   | 4   | 5   | 8   | 10  |
|----------------------|-----|-----|-----|-----|-----|
| Volume flow rate Q[l/s] | 4.85 | 8.28 | 12.47 | 10.44 | 9.43 |
Fig. 14 Influence of air pressure on thrust

Fig. 15 Influence of ejector inlet distance on thrust
5. CONCLUSIONS

In order to develop the bubble jet engine that is a new promotion system, the fundamental experiment was conducted and its practicality was estimated. The exhausted mass flow rate and velocity of water were achieved in water pumping test, and that output could be found. A horizontal type thrust measurement apparatus was done, and the influence of the ejector on thrust was investigated in various experimental conditions. As a result, at present, improvement in the thrust by putting an ejector cannot be gained.

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APPENDIX 1

Calibration of influence of the gravity on mass flow rate

Figure 17 indicates the difference in the velocity in case that gravity acts and doesn't. When the mass flow rate is found with void fraction measurement pipe, it is estimated lower than actual because of gravity. Specifically, the water flowed down through flow pipe due to the gravity is accelerated (Fig. 18(b)). The formula in acceleration in consideration of the influence of the gravity is:

\[ v_a = v_0 + gt_1 \] (7)

\[ h = v_0t_1 + \frac{gt_1^2}{2} \] (8)

where, \( v_a \) : velocity in consideration of the gravity, \( v_0 \) : velocity when gravity isn't taken into consideration, \( g \) : gravity acceleration, \( h \) : length of void measurement pipe.

Since \( v_a \) and \( h \) are well known here by equation (3), \( v_0 \) and \( t_1 \) can be looked for by the coalition.

Next, \( t_2 = \frac{h}{v_0} \), which is time to be necessary for water to fall in uniform velocity, is substituted for equation (8). Thus:

\[ h_a = v_0t_2 + \frac{gt_2^2}{2} \] (9)

Therefore, the mass flow rate in acceleration is modified to the mass flow rate in uniform velocity by finding out \( h_a \).

Fig. 17 difference from the mass flow rate in uniform velocity and in acceleration