
Original Paper (Invited)

Experimental Study on Performance of a Propulsive Nozzle with a Blower Piping System

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Abstract

The characteristics of the thrust for ship propulsion equipment directly driven by air compressed by pressure fluctuation in a blower piping system are investigated. The exhaust valve is positioned upon the air ejection hole in the discharge pipe in order to induce the large-scale pressure fluctuation, and the effects of the valve on the pressure in the pipes and the thrust for the propulsive nozzle are examined. The pressure in the pipes decreases immediately after the valve is opened, and it increases just before the valve is closed. The thrust for the propulsive nozzle monotonically increases with increasing number of revolutions and depth. The interfacial wave in the nozzle appears in the frequency of approximately 4Hz, and it is important for the increase of the thrust to synchronize the opening-closing cycle for the exhaust valve with the generation frequency of the interfacial wave. The finite difference lattice Boltzmann method is helpful to investigate the characteristics of the flow in the nozzle.

Keywords: Ship propulsion, water jet, pressure fluctuation, blower, pipe line, fluid machinery

1. Introduction

Tsutahara and Sakamoto et al. [1] developed a two-dimensional semi-open-type nozzle for ship propulsion equipment directly driven by high-pressure gas, and the investigation concerning the performance improvement has been done [2]. The developed nozzle opens its lower side to the water flow. The high-pressure gas is ejected into the nozzle and generates the propulsive force. The ejected gas phase and water-flow phase are separated clearly, and the water downstream is accelerated directly as the water jet [3, 4]. The principle of the acceleration for the water is essentially different from an ejector in which the water is accelerated by the conversion of momentum owing to the turbulent mixing. The developed nozzle is a simple structure, and it can work as the propulsion equipment with a simple substance.

Witte [5] and Mottard [6] proposed nozzle named the water ramjet as the propulsion equipment in the 1960s. Their proposed nozzles accelerate the water directly by ejecting high-pressure air into the nozzle. There were, however, no reports that these nozzles were actually applied to ship propulsion. Since their proposed equipment was of the axially symmetrical type, the water flows into the nozzle only from the upstream. As a result, the quantity of the water accelerated by ejecting the high-pressure air is not sufficient to obtain thrust, and it is thought that the propulsive efficiency was also small.

Although Tsutahara et al. [7, 8] have developed the improvement of the performance for the two-dimensional semi-open-type nozzle and have verified the effectiveness, the performance for the transient response in the propulsion system including the fluid machinery such as a compressor has not been considered to date. The blower piping system with the discharge opening under the surface of water induces the self-excited vibration because of the heaving of the gas-liquid interface at the certain depth of water of the discharge opening, and the pressure fluctuation is caused by the self-excited vibration [9]. At that time, the air compressed by the pressure fluctuation is periodically ejected dependent on the flow in the nozzle. As a result, the generating thrust increases, and the performance of the propulsive nozzle should be improved.

The purpose of this study is to investigate the characteristics of the thrust for the ship propulsion equipment directly driven by the air compressed by the pressure fluctuation in the blower piping system. The exhaust valve is positioned upon the air ejection hole in the discharge pipe in order to induce the large-scale pressure fluctuation, and the effects of the valve on the pressure in the pipes and the thrust for the propulsive nozzle are examined. These results are reported below.

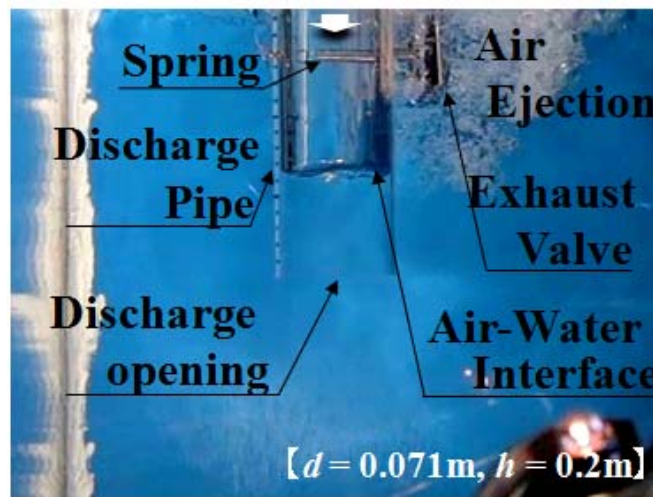
On the other hand, the propulsive nozzle is fixed at the discharge pipe as shown in Figure 1(b). The structure of the propulsive nozzle consists of the air ejection hole with the diameter of 30mm, the nozzle plate with the length of 200mm, and the side plate with the width of 71mm. The measurement of the thrust for the propulsive nozzle was carried out by using the strain gauge put on the supporting rod made of the stainless steel. A part of the duct in the discharge pipe is constructed with the duct horse. It is possible to move on the direction of the propulsion each time the thrust generates. The thrust for the propulsive nozzle were measured for various parameters such as the number of revolutions N for the blower, the opening angle θ of the nozzle plate, the depth h , and the opening-closing cycle f_E for the exhaust valve. When the exhaust valve is used, the air is ejected intermittently from the air ejection hole based on the opening-closing cycle. The discharge opening with the diameter of 71mm was used during measurement.

In order to observe the flow in the discharge pipe and the nozzle, the observation by using a high speed camera is done at the same time as measuring the pressure in the pipes.

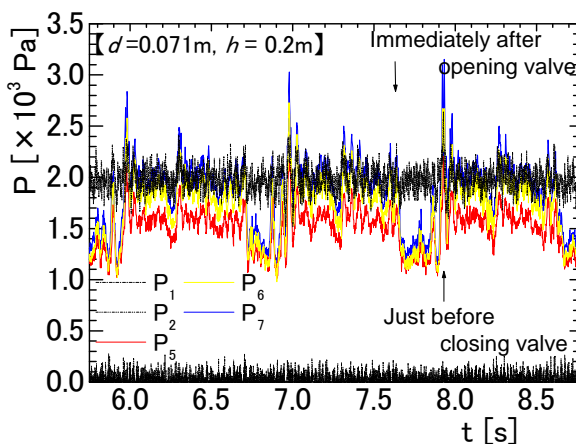
3. Experimental results and discussions

The flow in the discharge pipe for the blower piping system without the propulsive nozzle is shown in Figure 2(a) under the opening-closing cycle of 1Hz. The high-pressure air is ejected from the air ejection hole through the discharge pipe into the water, and the heaving of the gas-liquid interface occurs in the discharge pipe. The pressure in the pipes decreases immediately after the exhaust valve is opened, and it increases just before the valve is closed as shown in Figure 2(b). The time-averaged maximum value of the pressure fluctuation is approximately 1.3 times higher than that of the piping system without the exhaust valve. Then the dominant frequency of the pressure fluctuation appears in approximately the integral multiple of the period of the opening-closing cycle for the exhaust valve as shown in Figure 2(c).

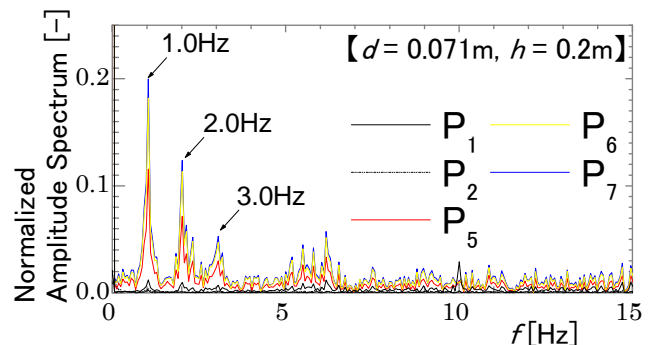
The effect of the opening-closing cycle on the pressure fluctuation is shown in Figure 3(a) and (b), respectively. The relative



(a) Flow in discharge pipe



(b) Time history of pressure



(c) Frequency analysis

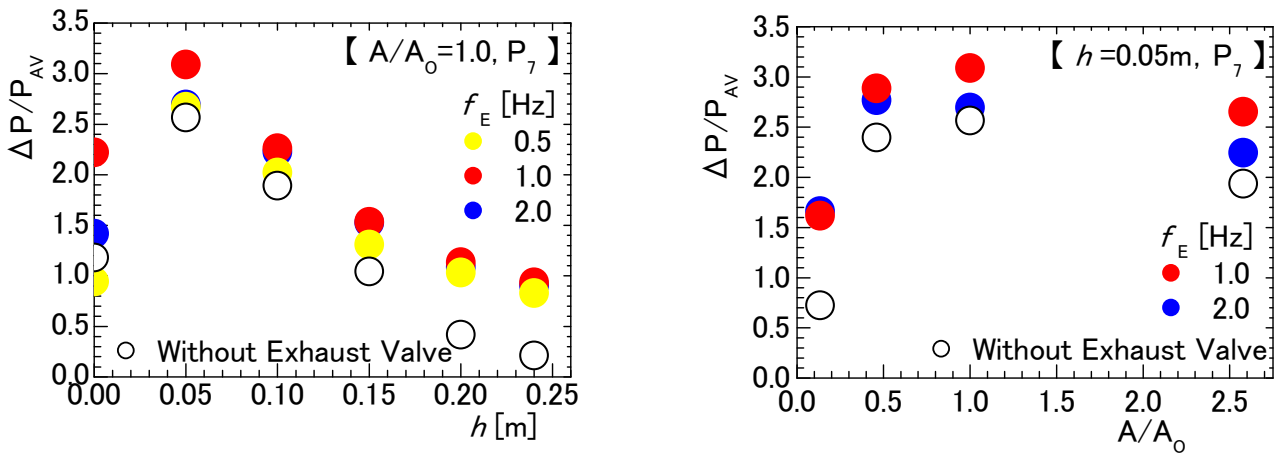
Fig. 2 Blower piping system with opening-closing cycle of 1Hz ($A/A_0 = 1.0$)

pressure pulsation $\Delta P/P_{AV}$ is defined as the ratio of the amplitude ΔP to the time-averaged pressure P_{AV} for the pressure fluctuation, and it means the strength of the pressure fluctuation. The amplitude ΔP is given by the averaged value of the amplitude extracted under the dominant frequency of the pressure fluctuation. The cross-section ratio A/A_0 is defined as the ratio

of the area A with the diameter of d to the area A_0 with the diameter of 71mm for the discharge opening. The relative pressure pulsation is higher than that obtained by the piping system without the exhaust valve. It is thought that the large-scale pressure fluctuation is caused by the self-excited vibration. The value of the relative pressure pulsation converges on the fixed value regardless of the opening-closing cycle under the deep depth or the small cross-section ratio.

The relationship between the thrust T for the propulsive nozzle and the number of revolutions N for the blower is shown in Figure 4. The exhaust valve is opened to its full angle during measurement, and the air is ejected continuously from the air ejection hole. The thrust increases monotonically with increasing number of revolutions. At that time, the periodic pressure fluctuations with the regular amplitude from the plenum chamber to the discharge pipe appeared in the pipes as shown in $P_5 - P_7$ of Figure 5(a). The flow in the nozzle during 0.25sec is shown in Figure 5(b). When the pressure in the discharge pipe is high, the ejected air becomes the mass of the air in the nozzle [Refer to $t=10.080s$ in Fig.5(b)]. The air phase and the water phase are separated clearly as reported in a previous paper [3]. At that time, the ejected air accelerates the water downstream. The interface of two-phases behaves like the interfacial wave of the water and the air [Refer to $t=10.105 - 10.145s$ in Fig.5(b)]. When the interfacial wave reaches the nozzle exit (i.e., water surface) [Refer to $t=10.245s$ in Fig.5(b)], the pressure in the discharge pipe decreases [Refer to trough part in pressure fluctuation for P_7 in Fig.5(a)]. Then flow rate of the ejection air also decreases [Refer to $t=10.330s$ in Fig.5(b)]. As a result, the flow in the nozzle repeats the same flow patterns with the period of approximately 0.25sec (i.e., 4Hz). The generation frequency of the interfacial wave is approximately equal to the dominant frequency of the pressure fluctuation in the discharge pipe as shown in Figure 5(c).

The relationship between the thrust T and the opening angle θ of the nozzle plate for the nozzle with the continuous air ejection is shown in Figure 6. The thrust increases monotonically with increasing opening angle of the nozzle plate. The main reason is that the component of the propulsive direction of the force acting upon the nozzle wall increases with increasing opening angle.



(a) Influence of depth h (b) Influence of cross-sectional area A
Fig. 3 Effects of opening-closing cycle f_E on relative pressure pulsation $\Delta P/P_{AV}$

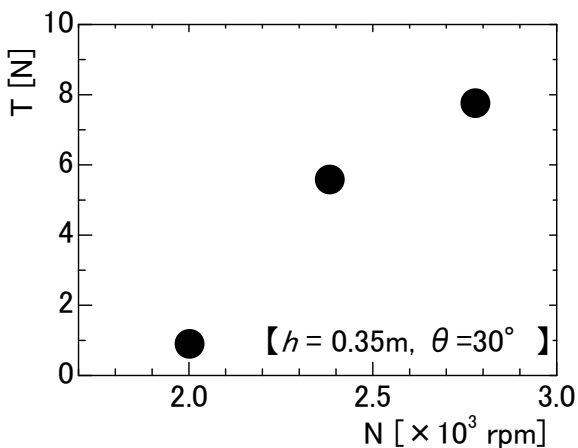


Fig. 4 Relationship between thrust T and number of revolutions N for nozzle with continuous air ejection

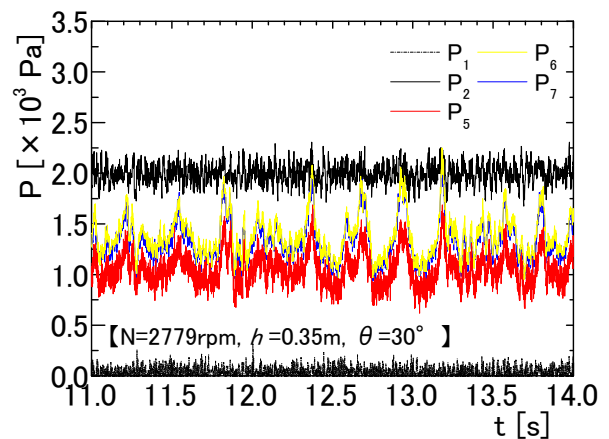
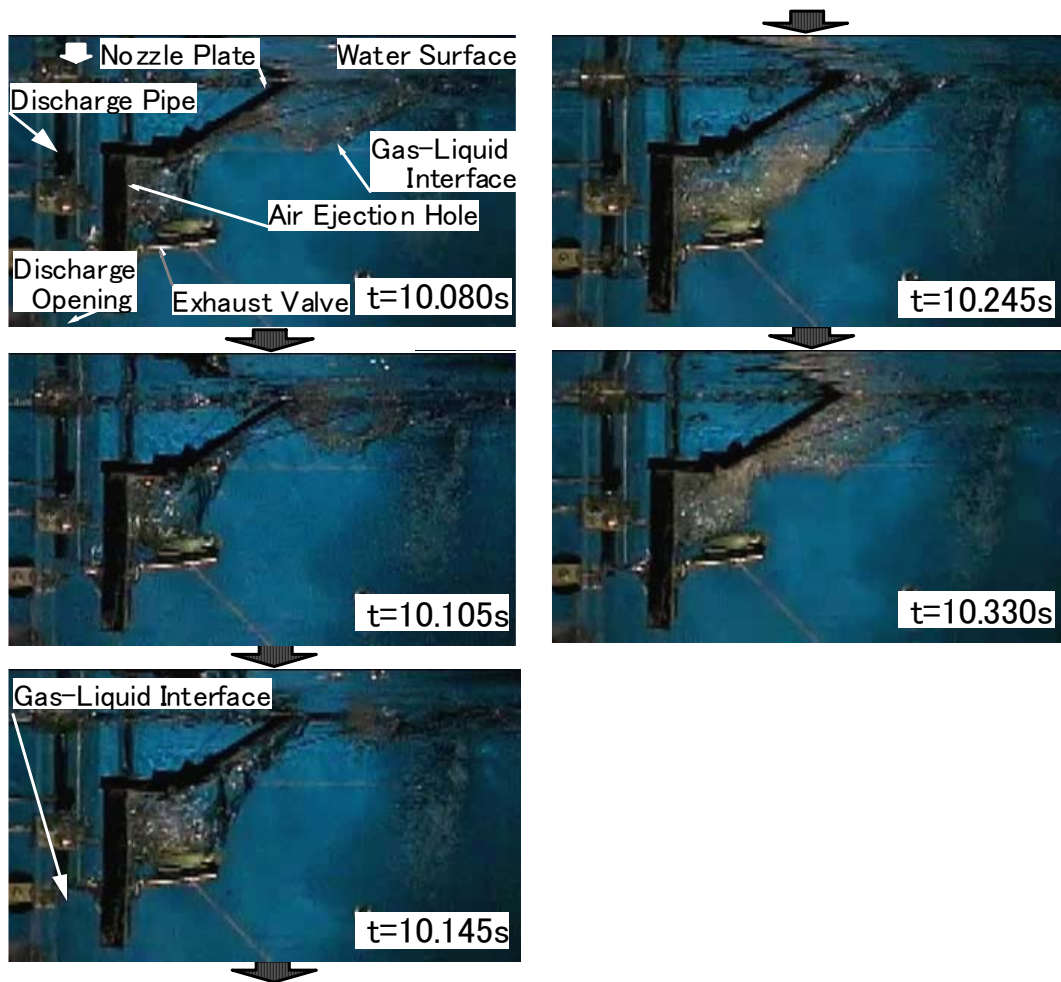
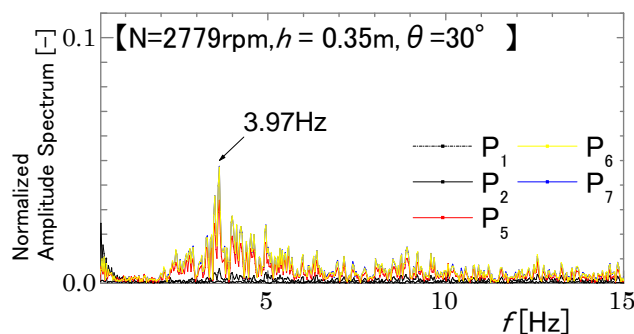


Fig. 5(a) Time history of pressure



(b) Flow in nozzle [N=2779rpm, $h=0.35\text{m}$, $\theta=30^\circ$]



(c) Frequency analysis

Fig. 5 Pressure fluctuation in the pipes and flow in nozzle with continuous air ejection

Figure 7 shows the relationships between the modified thrust T_M and the depth of the water h of the discharge opening. The modified thrust is defined as the ratio of the measured thrust to the air ejection time rate. The air ejection time rate is defined as the ratio of the air ejection duration time to the measuring time of the thrust. When the air is ejected continuously, the modified thrust equals the measured thrust. When the air is ejected intermittently, the air ejection duration time is 0.39sec per opening-closing cycle of 1Hz. Hence, the modified thrust equals 2.56 times of the measured thrust. The results of both the intermittent air ejection and the continuous air ejection increase with increasing depth. This is considered to be due to the increase of the quantity of the water accelerated by the high-pressure air. The modified thrust of the nozzle with the intermittent air ejection is higher than that of the nozzle with the continuous air ejection within the limits of the experiment.

The flow in the nozzle with the intermittent air ejection (Opening-closing cycle of 1Hz, Air ejection duration time of 0.39sec) during 0.345sec is shown in Figure 8. The quiescent time of the air ejection is 0.61sec, and the period of the time is longer than that of the generation of the interfacial wave. For that reason, the nozzle just before the air ejection was filled with water each time the valve opens [Refer to $t=24.145\text{s}$ in Fig.8]. When the exhaust valve begins to open, the mass of the air accelerates the water [Refer to $t=24.205\text{s}$ in Fig.8] while the pressure in the discharge pipe begins to decrease [Refer to P_7 in Fig.9(a)]. After the

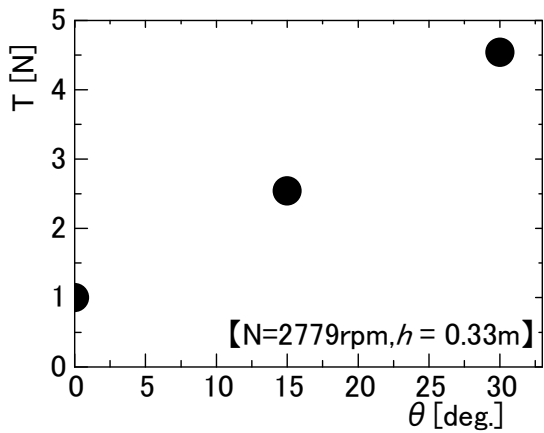


Fig. 6 Relationship between thrust T and opening angle θ of nozzle plate for nozzle with continuous air ejection

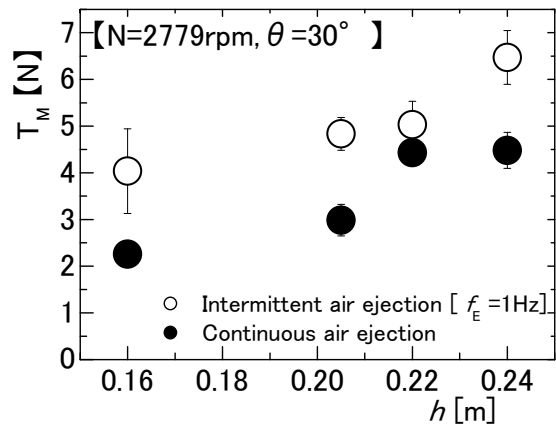


Fig. 7 Relationships between modified thrust T_M and depth h of discharge opening

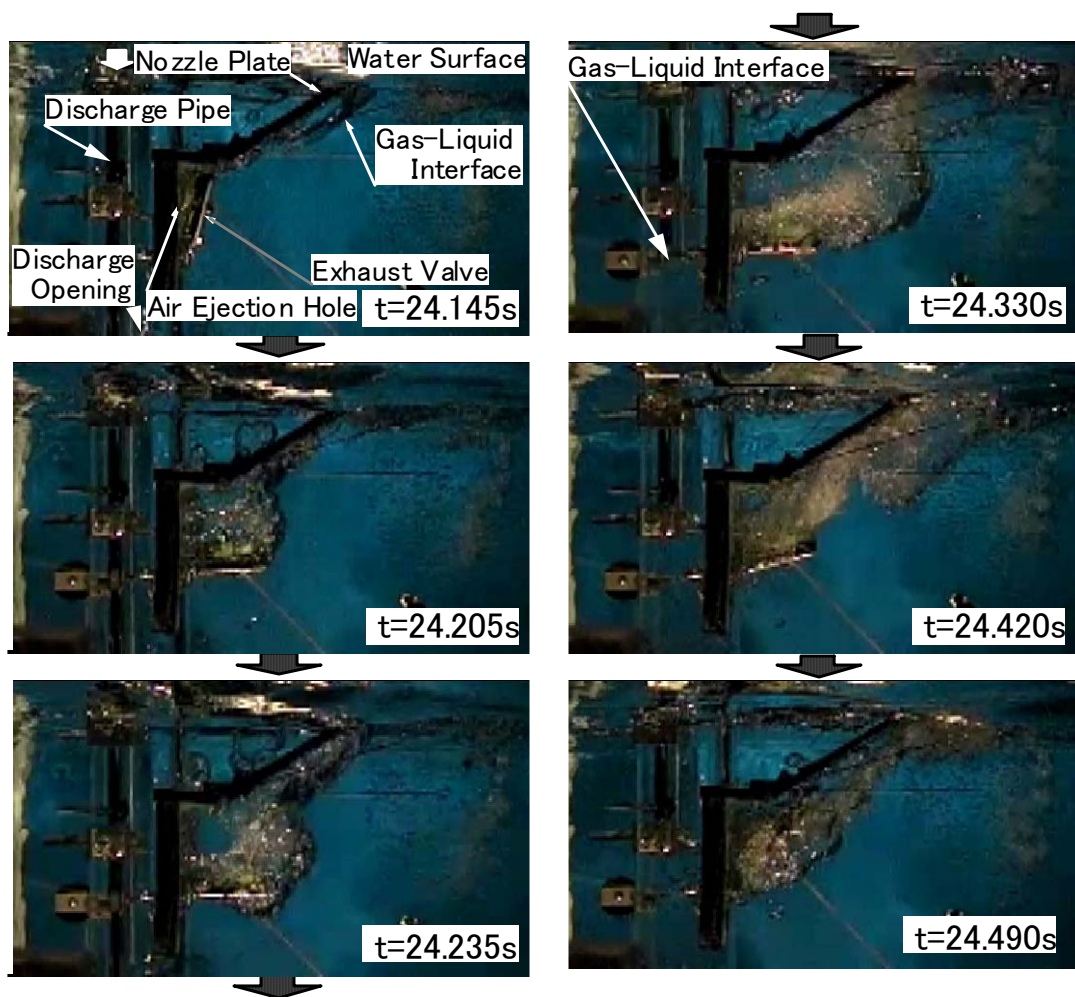
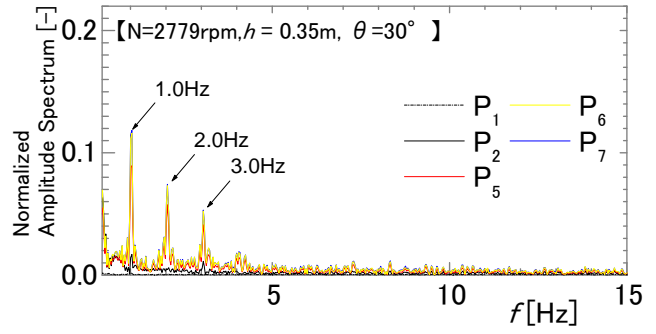
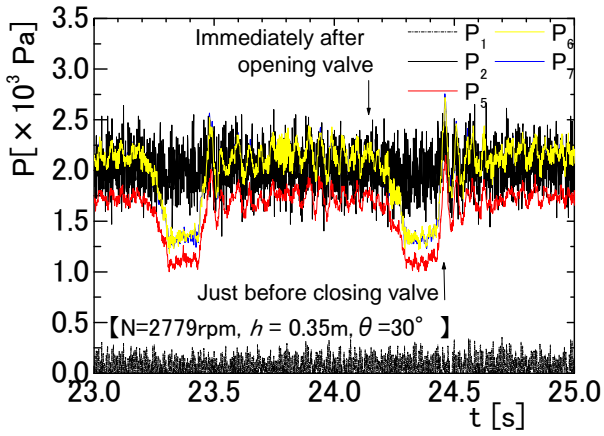


Fig. 8 Flow in nozzle with intermittent air ejection of $f_E=1\text{Hz}$ [$N=2779\text{rpm}$, $h=0.35\text{m}$, $\theta=30^\circ$]

exhaust valve was opened, the flow in the nozzle showed the similar results as those of Fig.5(b) obtained by the nozzle with the continuous air ejection [Refer to $t=24.235 - 24.420\text{s}$ in Fig.8]. And then, the pressure in the discharge pipe suddenly increases owing to the phenomenon of water hammer just before the valve is closed [Refer to P_5-P_7 in Fig.9(a)]. The air of the considerable volume leaks out through a few gaps of the exhaust valve [Refer to $t=24.490\text{s}$ in Fig.8]. The dominant frequency of the pressure fluctuation in the pipes appeared in the integral multiple of the period of the opening-closing cycle as shown in Figure 9(b). It is considered to be important for the increase of the thrust to synchronize the opening-closing cycle for the exhaust valve with the generation frequency of the interfacial wave in the nozzle. The development of the opening-closing cycle, the disposition, and the number for the valve must be done in order to obtain the air of the high pressure effectively.



(a) Time history of pressure

(b) Frequency analysis

Fig. 9 Pressure fluctuation in pipes for nozzle with intermittent air ejection of $f_E=1\text{Hz}$

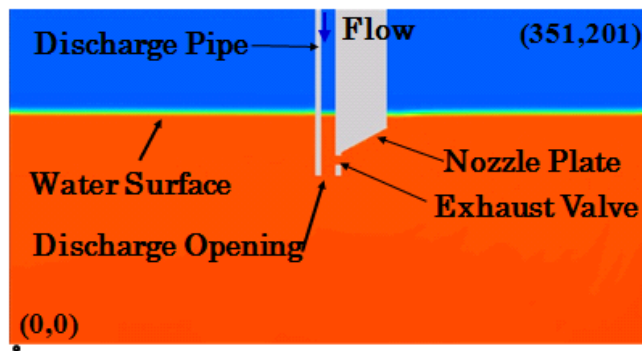


Fig. 10 Calculation model

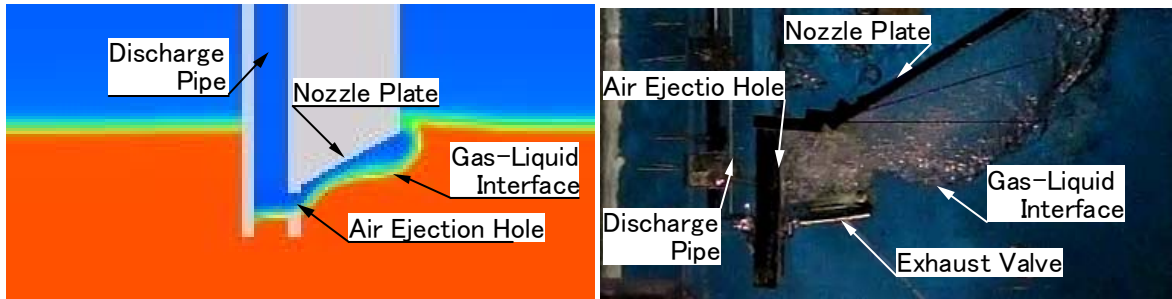


Fig. 11 Flow in nozzle [$\theta = 30^\circ$]

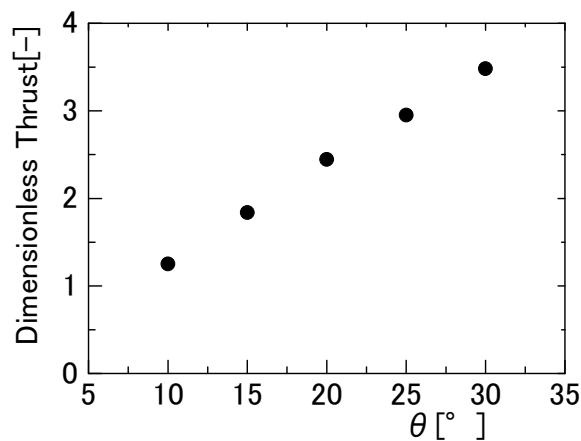


Fig. 12 Calculation results of dimensionless thrust for opening angle θ of nozzle plate

4. Calculation

The calculation of the flow in the propulsive nozzle was carried out by the scheme of 2-particles thermal-fluid model for the finite difference lattice Boltzmann method. The calculation code including the modification models such as the phase separation, the surface tension, and the high density ratio acceleration modification developed by Tsutahara et al. [10] has been used for the present flow. The lattice points of 351×201 are used in this calculation as shown in Figure 10, and the nonslip condition is used for the nozzle wall. The gas flows from upper side in the discharge pipe, and it is ejected continuously from the air ejection hole through the discharge pipe into the nozzle.

The calculation result of the flow in the nozzle is shown in Figure 11. The interfacial wave of the two-phases generates in the nozzle like the result of the experiment. Figure 12 shows the calculation results of the dimensionless thrust for the opening angle θ of the nozzle plate. The dimensionless thrust is obtained by the sum of the propulsive direction component of the force acting upon the nozzle wall. The dimensionless thrust increases with increasing opening angle. These calculation results agree qualitatively with those obtained by the experiment, and the present calculation is effective to investigate the characteristics of the flow in the propulsive nozzle.

5. Conclusions

The characteristics of the thrust for the ship propulsion equipment directly driven by the air compressed by the pressure fluctuation in the blower piping system are investigated. The exhaust valve is positioned upon the air ejection hole in the discharge pipe in order to induce the large-scale pressure fluctuation, and the effects of the valve on the pressure in the pipes and the thrust for the propulsive nozzle are examined. The following results were obtained:

- (1) The pressure in the pipes decreases immediately after the valve is opened, and it increases just before the valve is closed. The dominant frequency of the pressure fluctuation in the pipes agrees with that of the opening-closing cycle for the exhaust valve.
- (2) The thrust for the propulsive nozzle monotonically increases with increasing number of revolutions and depth.
- (3) The interfacial wave in the nozzle appears in the frequency of approximately 4Hz, and it is important for the increase of the thrust to synchronize the opening-closing cycle for the exhaust valve with the generation frequency of the interfacial wave.
- (4) The finite difference lattice Boltzmann method is helpful to investigate the characteristics of the flow in the nozzle.

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Nomenclature

h	Depth of water of discharge opening [m]	A	Area with diameter of d [m ²]
d	Diameter of discharge opening [m]	A_O	Area with diameter of 71mm [m ²]
θ	Opening angle of nozzle plate [°]	A/A_O	Cross-section ratio at discharge opening [-]
P	Pressure [Pa]	t	Time [sec]
ΔP	Amplitude of pressure fluctuation [Pa]	f	Frequency [Hz]
P_{AV}	Time-averaged value of pressure fluctuation [Pa]	f_E	Opening-closing cycle for exhaust valve [Hz]
$\Delta P/P_{AV}$	Relative pressure pulsation in pipe [-]	T	Thrust for propulsive nozzle [N]
N	Number of revolutions [rpm]	T_M	Modified thrust for propulsive nozzle [N] (= T / Air ejection time rate)

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