
Original Paper

Effects of the Air Volume in the Air Chamber on the Performance of Water Hammer Pump System

Sumio Saito¹, Masaaki Takahashi² and Yoshimi Nagata³

¹Department of Mechanical Engineering, Tokyo National College of Technology,
1220-2 Kunugida-machi, Hachioji-shi, Tokyo, 193-0997, Japan

²Mechanical and Computer Systems Engineering, Advanced Engineering Course,
Tokyo National College of Technology,

1220-2 Kunugida-machi, Hachioji-shi, Tokyo, 193-0997, Japan

³Yamaha Motor Engineering Co., Ltd.

Abstract

Recently, as global-scale problems, such as global warming and energy depletion, have attracted attention, the importance of future environmental preservation has been emphasized worldwide, and various measures have been proposed and implemented. This study focuses on water hammer pumps that can effectively use the water hammer phenomenon and allow fluid transport without drive sources, such as electric motors. An understanding of operating conditions of water hammer pumps and an evaluation of their basic hydrodynamic characteristics are significant for determining whether they can be widely used as an energy-saving device in the future. However, conventional studies have not described the pump performance in terms of pump head and flow rate, common measures indicating the performance of pumps. As a first stage for the understanding of water hammer pump performance in comparison to the characteristics of typical turbo pumps, the previous study focused on understanding the basic hydrodynamic characteristics of water hammer pumps and experimentally examined how the hydrodynamic characteristics were affected by the inner diameters of the drive and lift pipes and the angle of the drive pipe. This paper suggests the effect of the air volume in the air chamber that affects the hydrodynamic characteristics and operating conditions of the water hammer pump.

Keywords: Water Hammer Pump, Fluid Transients, Pump Performance, Pressure Fluctuation, Flow Visualization

1. Introduction

Recently, as global-scale problems, such as global warming and desertification, have attracted attention, the importance of future environmental preservation has been emphasized worldwide, and various measures have been proposed and implemented. In the field of energy- and life-related technology, a variety of fluid machines play an important role in the infrastructure of society, and more energy-saving and resource-saving machinery will be needed.

Water hammer pumps effectively use the water hammer phenomenon, which imposes a problem in fluid pipeline networks including pumps, and allow fluid transport without drive sources, such as electric motors. They have been proposed and made in various sizes and configurations, mainly for educational purposes [1], [2], [3].

In addition, the results of experiments that examined the effect of the geometric form of water hammer pumps by varying the length and angle of the drive pipe, the water level in the water tank, and the weight and lift of the drain valve have been reported [4], [5]. A paper has also been published analyzing the water hammer phenomenon numerically by using the characteristic curve method for comparison with experimental results [6]. However, these conventional studies have not fully evaluated the pump performance in terms of pump head and flow rate, common measures indicating the performance of pumps.

With this being the situation, as a first stage for the understanding of water hammer pump performance in comparison to the characteristics of typical turbo pumps, the previous study [7] experimentally examined how the basic hydrodynamic characteristics were affected by the inner diameters of the drive and lift pipes, the form of the air chamber, and the angle of the drive pipe, which are believed to be representative geometric form factors of water hammer pumps. Focusing on the behavior around the drain valve affecting the characteristics of water hammer pumps, the previous study also clarified the effect of the length of the spring attached to the drain valve [8].

Based on these results, this study examines the relationship between the temporal pressure fluctuations in the valve and air

chambers at different air volumes in the air chamber and the performance of the water hammer pump to elucidate the behavior around the valve and air chambers that affects the operating conditions of the water hammer pump.

2. Experimental Apparatus and Method

2.1 Experimental Apparatus

Figure 1 shows an overall schematic diagram of the water hammer pump system used for the experiment. Figure 2 shows a detailed schematic diagram of the water hammer pump, including the valve chamber and its associated parts. The pump is composed of main parts from the water tank (1) to the spring (8).

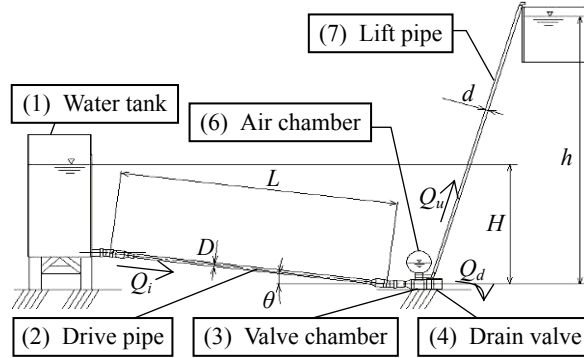


Fig. 1 Water hammer pump system

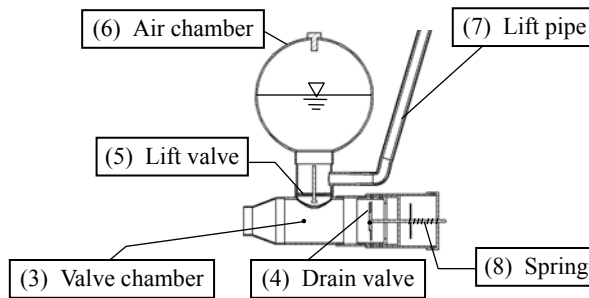


Fig. 2 Main parts of the water hammer pump

The drive pipe (2), which supplies water from the water tank (1) to the valve chamber (3), is made of acrylic resin material to allow the visualization of internal flow. The valve chamber (3) and the air chamber (6) are also made of acrylic resin material and configured so that ink can be injected for the visualization of flow in the valve chamber. The air chamber is spherical in shape to withstand high pressures.

The operation of the drain valve (4) located downstream of the valve chamber (3) causes the water hammer phenomenon, which in turn lifts water through the lift valve (5). Although the drain pipe angle θ_d is adjustable with an elbow attached to the drain valve (4), the experiment was conducted by fixing θ_d at 0 [°]. For the water hammer phenomenon to occur, the drain valve must open to allow the flow of water through the drive pipe into the valve chamber. Therefore, the spring (8) (spring length $\ell_s = 46.7$ [mm]) is provided downstream of the drain valve (4) to bias the valve open.

2.2 Experimental Conditions and Geometric Form Factors

Table 1 shows the factors that affect the hydrodynamic characteristics of the water hammer pump. For this experiment, four different air volumes were used in the air chamber, while the drive pipe inner diameter and the lift pipe inner diameter were set at $D = 25$ [mmφ] and $d = 18$ [mmφ], to examine the effect of the air volume on the performance of the water hammer pump.

The drive pipe length was set at $L = 4$ [m], and the drive pipe angle was set at $\theta = 7$ [°] with reference to the results of the previous study [7]. The water level, which is equal to the height between the water level in the water tank (1) and the valve chamber (3), was fixed at $H = 0.5$ [m].

The performance of the water hammer pump is indicated in terms of the relationship between the lifted flow rate Q_u and the pump head h , like the performance of typical turbo pumps. The pump efficiency η is determined using the following equation to take into consideration the input and output flow rates of the water hammer pump [7], [8].

$$\eta = \frac{Q_u \times h}{Q_i \times H} = \frac{Q_u}{Q_d + Q_u} \times \frac{h}{H} \quad [\%] \quad (1)$$

Table 1 Experimental factors of the water hammer pump

Geometrical form factor		Experimental condition
Drive pipe inner diameter	D [mm ϕ]	25
Drive pipe length	L [m]	4
Drive pipe angle	θ [$^\circ$]	7
Drain pipe angle	θ_d [$^\circ$]	0
Lift pipe inner diameter	d [mm ϕ]	18
Water level	H [m]	0.5
Air chamber capacity	V [l]	3.85 (Spherical type)
Air volume in the air chamber	V_a [l]	0, 0.356, 1.94, 3.76
Spring length	ℓ_s [mm]	46.7
Spring constant	k [N/mm]	0.122

2.3 Experimental Method

The input flow rate Q_i into the water hammer pump was determined by measuring the flow rate entering the water tank (1) while keeping the water level in the tank constant. In addition, the lift pipe outlet was positioned so as to obtain the desired pump head; the outlet flow rate was measured by a gravimetric method to determine the lifted flow rate Q_u . The flow rate from the drain valve Q_d was also measured directly by the gravimetric method. The measurement of each flow rate was conducted for as long time as possible to minimize errors caused by flow fluctuations.

To elucidate the hydrodynamic behavior of the water hammer pump, temporal fluctuations in the pressure P_a in the air chamber (6) and the pressure P_v in the valve chamber (3) as shown in Figure 2 were measured using a strain gauge type pressure transducer (PGM-1KG, manufactured by Kyowa Electronic Instruments Co., Ltd.) and recorded using an amplifier and an AD converter. For the behavior of flow in the valve chamber, the internal flow was visualized and observed by injecting ink upstream of the valve chamber.

3. Experimental Results and Discussion

3.1 Changes in Water Hammer Pump Performance at Different Air Volumes in the Air Chamber

Figure 3 shows the water hammer pump performance measured at four different air volumes in the air chamber ($V_a = 0, 0.356, 1.94,$ and 3.76 [l]). As in the case for turbo pump performance, the first quadrant indicates the relationship between the pump head h and the lifted flow rate Q_u in solid lines and the relationship between the pump efficiency η and the lifted flow rate Q_u in dotted lines. As performance measures specific to water hammer pumps, the second and fourth quadrants show the relationship between the pump head h and the number of water hammer occurrences C and the relationship between the drain flow rate Q_d and the lifted flow rate Q_u , respectively.

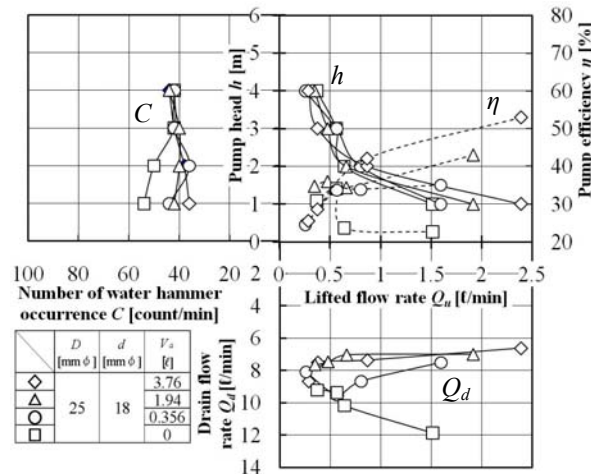


Fig. 3 Changes in water hammer pump performance at different air volumes in the air chamber

In the first quadrant, the relationship between the pump head h and the lifted flow rate Q_u is represented by downward-sloping curves similar to typical pump performance curves. As seen from the figure, the curves are flatter at higher levels of V_a (steeper at lower levels of V_a). The curves intersect in the vicinity of $Q_u = 0.6$ to 0.7 [l/min].

The relationship between the pump efficiency η and the lifted flow rate Q_u is represented by upward-sloping curves, except in the case of $V_a = 0$ [l]. The pump efficiency is higher at higher levels of V_a .

The fourth quadrant represents the relationship between the drain flow rate Q_d and the lifted flow rate Q_u . Only when $V_a = 0$ [l], the drain flow rate increases as the lifted flow rate increases. According to the above-mentioned equation (1), the drain flow rate Q_d is a component of the input flow rate and significantly affects the pump efficiency η . Thus, when $V_a = 0$ [l], the pump

efficiency decreases as the drain flow rate increases. Except in the case of $V_a = 0$ [ℓ], the drain flow rate is lower at higher levels of V_a and remains almost constant regardless of the lifted flow rates Q_u .

In the second quadrant, the number of water hammer occurrences C is around 40 [count/min] regardless of the pump head h . Only when $V_a = 0$ [ℓ], the number of water hammer occurrences C increases at a low pump head of $h = 1$ to 2 [m]. This fact suggests that, when $V_a = 0$ [ℓ], the drain flow rate Q_d increases with an increase in the number of water hammer occurrences C .

3.2 Temporal Pressure Fluctuations in Valve and Air Chambers of Water Hammer Pump

3.2.1 Operating Principle of Water Hammer Pump

For the four levels of V_a , Figures 4 and 5 show temporal fluctuations in the valve chamber pressure P_v and the air chamber pressure P_a during water hammer pump operation at pump heads of $h = 2$ and 4 [m]. These figures also indicate the water hammer occurrence interval ΔT , the pressure holding time during lifting operation Δt , and peak pressures.

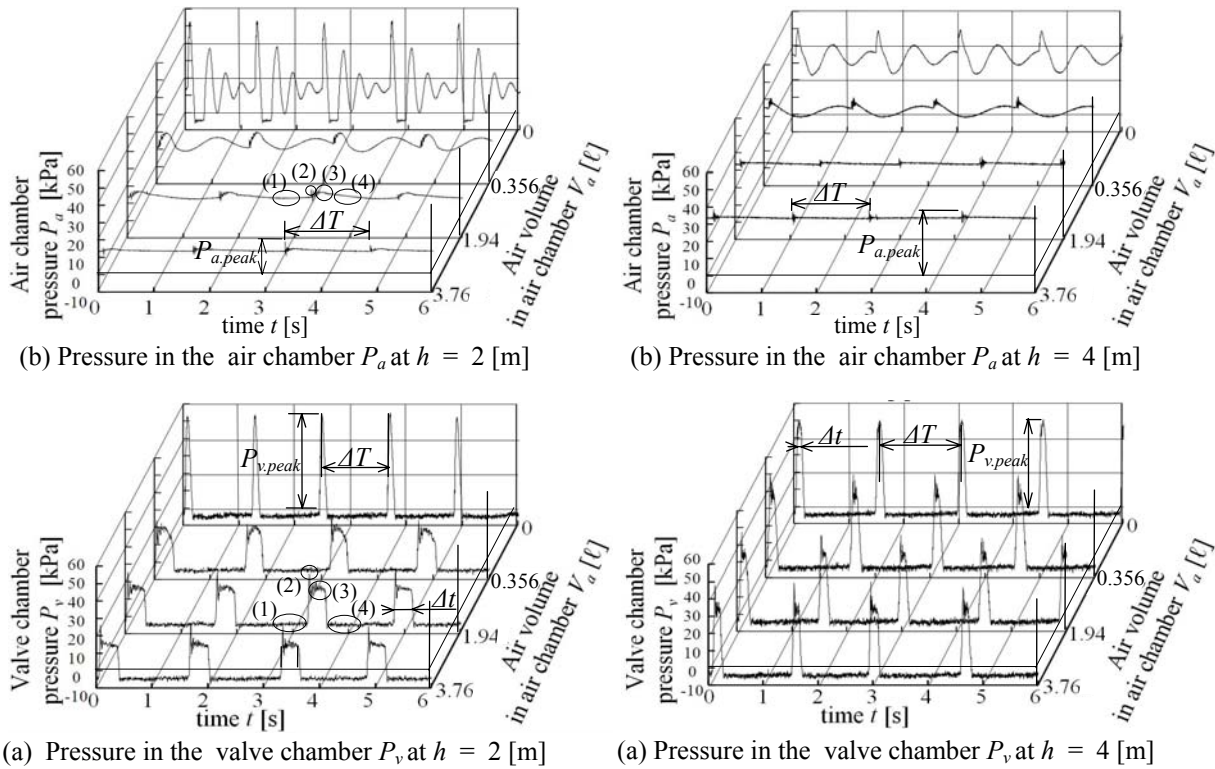


Fig. 4 Pressure fluctuations at different levels of V_a at $h=2$ [m] **Fig. 5** Pressure fluctuations at different levels of V_a at $h=4$ [m]

The numbers (1) to (4) in Figure 4 correspond to the phases of water hammer pump operation schematically illustrated in Figure 6. The operation of the pump is detailed below.

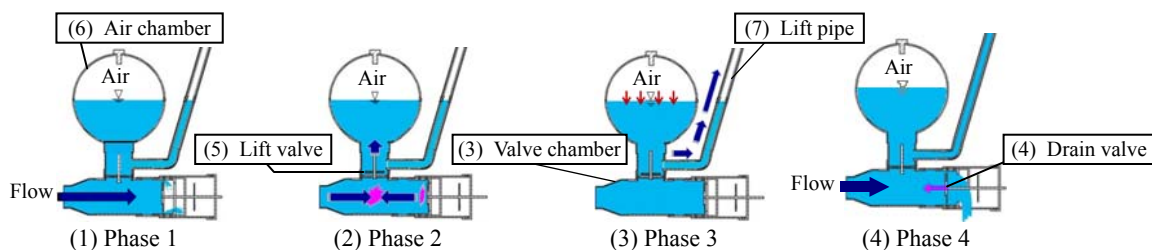


Fig. 6 Water hammer pump operation

(1) Phase 1: Water is supplied from the water tank (1), a water source that maintains a constant water level, through the drive pipe (2) into the valve chamber (3). In this phase, the valve chamber pressure is negative, and the air chamber pressure decreases gradually.

(2) Phase 2: The water flowing into the valve chamber in Phase 1 causes the drain valve (4) located downstream of the valve chamber (3) to close rapidly and induce the water hammer phenomenon. The valve chamber pressure rises rapidly and opens the lift valve (5), allowing a portion of the water to flow into the air chamber (6). Accordingly, the air chamber pressure also rises abruptly.

(3) Phase 3: As the compression effect is caused by the internal air volume, the water flowing into the air chamber (6) is lifted up through the lift pipe (7) to a position higher than the water source. In this phase, the lift valve (5) remains open.

(4) Phase 4: The lift valve (5) closes after the lifting operation is complete. At the same time, the pressure in the valve chamber (3) decreases to a negative value. With this negative pressure and the spring force, the drain valve (4) opens. Afterward, water from the tank flows into the valve chamber again, and Phases 1 to 4 are repeated automatically.

3.2.2 Pressure Fluctuations in the Valve and Air Chambers at Different Pump Heads and Visualization of Flow around the Valve Chamber

(a) Behavior of the water hammer pump at a pump head of $h = 2$ [m]

Figure 4 (a) and (b) show temporal pressure fluctuations in the valve and air chambers at different air volumes in the air chamber V_a at a pump head of $h = 2$ [m].

In Figure 4 (a), the waveform of the pressure in the valve chamber is extremely sharp at $V_a = 0$ [ℓ], which represents that the air chamber is completely filled with water. At higher levels of V_a , the peak pressure is lower, and the pressure holding time during lifting operation Δt is longer.

In Figure 4 (b), the decrease in the air chamber pressure after $P_{a,peak}$ is smaller at higher levels of V_a .

When $V_a = 0$ [ℓ], a specific waveform with the largest pressure fluctuations is observed; after $P_{a,peak}$, the pressure decreases rapidly to a negative value. The observation of the behavior in the valve chamber under this condition shows that, after the air chamber pressure reaches $P_{a,peak}$ and then decreases sharply, the lift valve remains open until the pressure starts to increase again, allowing water to flow into the air chamber.

For the four levels of V_a , Figure 7 shows the behavior of flow around the valve chamber during Phase 2 of water hammer pump operation at a pump head of $h = 2$ [m]. The opening degree of the lift valve (5) indicated by a dotted circle increases at higher levels of V_a . This observation agrees with the fact that the pressure holding time during lifting operation Δt increases at higher levels of V_a , as shown in Figure 4 (a).

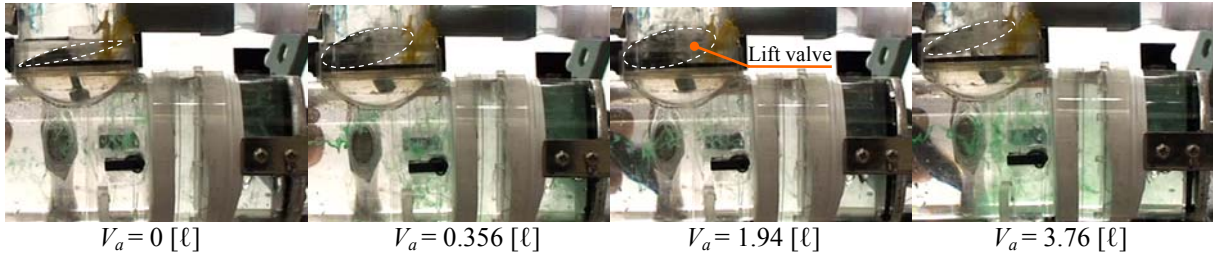


Fig. 7 Visualization of flow around the valve chamber at $h = 2$ [m]

(b) Behavior of the water hammer pump at a pump head of $h = 4$ [m]

At all levels of V_a in Figure 5 (a), the peak pressure in the valve chamber is higher, and the pressure holding time during lifting operation Δt is shorter, compared to the temporal pressure fluctuations in the valve chamber at a pump head of $h = 2$ [m] as shown in Figure 4 (a).

Figure 5 (b) shows that, at $V_a = 3.76$ and 1.94 [ℓ], the air chamber pressure fluctuates instantaneously during Phase 2 and that the subsequent pressure fluctuations are small. The pressure fluctuations are larger at lower levels of V_a .

Similar to Figure 7, Figure 8 visualizes the behavior of flow around the valve chamber during Phase 2 of water hammer pump operation at a pump head of $h = 4$ [m] for the four levels of V_a .

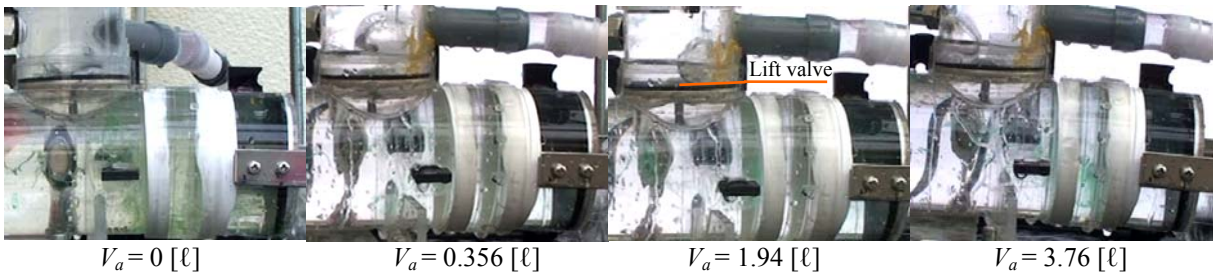


Fig. 8 Visualization of flow around the valve chamber at $h = 4$ [m]

At a pump head of $h = 4$ [m], the lift valve (5) works instantly in Phase 2, unlike the case of $h = 2$ [m]. Thus, the opening degree of the lift valve (5) shown in these photos is almost the same regardless of the level of V_a .

A comparison of the valve and air chamber pressures according to the pump head finds differences in peak pressure and lift valve operating conditions. However, basically, it demonstrates water hammer pump operation as shown in Figure 6.

3.2.3 Effects of the Air Volume in the Air Chamber on Pressure Behavior in the Valve and Air Chambers

Based on the results presented above, Figures 9 and 10 indicate the effects of the air volume in the air chamber on the peak pressure in the valve chamber $P_{v,peak}$ and the peak pressure in the air chamber $P_{a,peak}$ at each pump head.

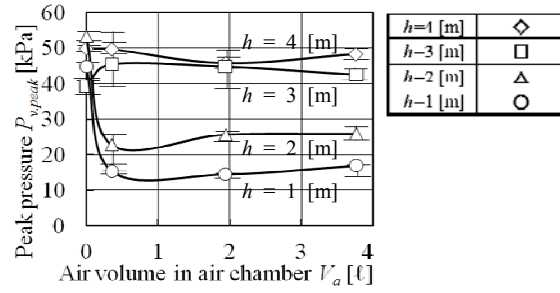


Fig. 9 Relationship between the peak pressure in the valve chamber $P_{v,peak}$ and the air volume in the air chamber V_a

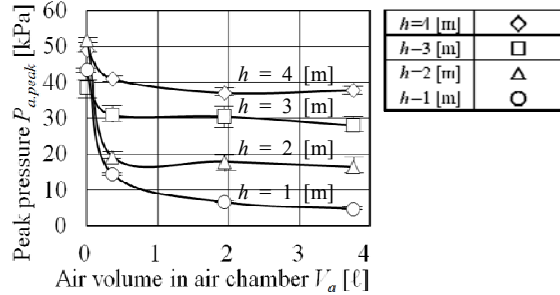


Fig. 10 Relationship between the peak pressure in the air chamber $P_{a,peak}$ and the air volume in the air chamber V_a

Figure 9 shows that, at low pump heads of $h = 1$ and 2 [m], the peak pressure in the valve chamber $P_{v,peak}$ tends to decrease as the level of V_a increases. The peak pressure decreases sharply in the presence of only a small amount of air, e.g. $V_a = 0.356$ [ℓ]. At high pump heads of $h = 3$ and 4 [m], the pressure fluctuates little and remains almost constant regardless of the air volume.

In Figure 10, the peak pressure in the air chamber $P_{a,peak}$ decreases as the level of V_a increases, regardless of the pump head. The decrease is more significant at lower pump heads.

The peak pressure is higher at higher pump heads. At $h = 4$ [m], however, the peak pressure fluctuations due to the difference in the level of V_a are small.

Figure 11 indicates the relationship between the pressure holding time during lifting operation Δt in the valve chamber and the air volume in the air chamber V_a at each pump head.

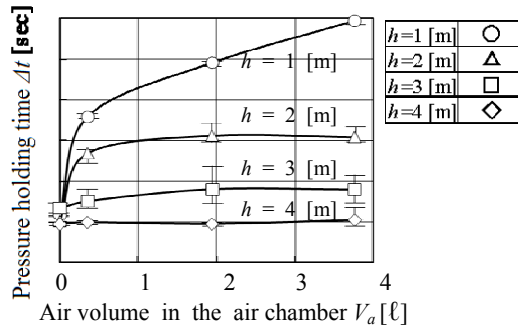


Fig. 11 Relationship between the pressure holding time during lifting operation Δt in the valve chamber and the air volume in the air chamber V_a

Figure 11 shows that the effect of V_a on the pressure holding time during lifting operation Δt in the valve chamber is the most significant at a low pump head of $h = 1$ [m]. At higher pump heads, the value of Δt remains almost constant regardless of the air volume.

At all pump heads, the pressure holding time during lifting operation Δt is the shortest at $V_a = 0$ [ℓ], which represents that the air chamber is completely filled with water. This observation agrees with the fact that the peak pressure is generally high at $V_a = 0$ [ℓ], as shown in Figures 9 and 10.

Combining these findings with those from Figures 9 and 10 reveals that, at $V_a = 0$ [ℓ], the peak pressure in the valve chamber fluctuates largely and sharply regardless of the pump head. At lower pump heads, the effect of V_a on the increase in the pressure holding time during lifting operation Δt is greater. Thus, the lifting of water may be facilitated by the compression effect of air in the air chamber.

4. Conclusions

The relationship between the temporal pressure fluctuations in the valve and air chambers at different air volumes in the air chamber and the performance of the water hammer pump has been examined to elucidate the behavior around the valve and air chambers that affects the operating conditions of the water hammer pump.

This study has yielded the following findings.

(1) The pump head vs. flow rate curves are flatter at higher levels of air volume in the air chamber V_a (steeper at lower levels of V_a). The pump efficiency η generally rises as the level of V_a increases.

(2) The peak pressures in the valve and air chambers vary depending on the pump head. However, the visualization of flow around the valve chamber has revealed that, basically, the operations in Phases 1 to 4 are repeated regardless of the pump head.

(3) The peak pressure in the valve chamber $P_{v,peak}$ and the peak pressure in the air chamber $P_{a,peak}$ tend to decrease as the air volume in the air chamber V_a increases. The fluctuations are more significant at lower pump heads.

(4) The effect of the air volume in the air chamber V_a on the pressure holding time during lifting operation Δt in the valve chamber is more significant at lower pump heads. Regardless of the air volume, the value of Δt remains almost constant at higher pump heads.

Nomenclature

C	Number of water hammer occurrences [count/min]	Q_i	Input flow rate [ℓ /min]
D	Drive pipe inner diameter [mm ϕ]	Q_u	Lifted flow rate [ℓ /min]
d	Lift pipe inner diameter [mm ϕ]	ΔT	Water hammer occurrence interval [s]
H	Water level [m]	Δt	Pressure holding time during lifting operation [s]
h	Pump head [m]	V	Air chamber capacity [ℓ]
L	Drive pipe length [m]	V_a	Air volume in the air chamber [ℓ]
ℓ_s	Spring length [mm]	θ	Drive pipe angle [$^\circ$]
P_a	Pressure in the air chamber [kPa]	θ_d	Drain pipe angle [$^\circ$]
P_v	Pressure in the valve chamber [kPa]	η	Pump efficiency (see Equation (1).) [%]
Q_d	Drain flow rate [ℓ /min]	$peak$	Peak pressure (subscript)

References

- [1] Kagami, Kenichi, IDE, Tsutomu, and Ushiyama, Izumi, 2001, Water hammer pump production handbook, p. 47, POWERSHA Inc.
- [2] Yunoki, Tomoya, 2004, "Production of a Hydraulic Ram Pump and its Research on its Characteristic," Japan Society for Science Education, Vol. 28, No. 2, pp. 94-100.
- [3] Abi Awoke Tessema, "Hydraulic Ram Pump System Design and Application," Proceedings of ESME 5th Annual Conference on Manufacturing and Process Industry, September 2000, pp. 1-8.
- [4] Hasegawa, Shigeo, Suehiro, Hakaru, and Yamaguchi, Kenji, 1984, "Trial of Hydraulic Ram and Its Performance Characteristics," Research Reports of Toyota College of Technology, No. 17, pp. 15-20.
- [5] Teferi Taye, Hydraulic Ram Pump, Journal of the ESME, Vol. II, No. 1, 1998-7, pp. 1-11.
- [6] Okada, Uetuki, and Takenaka, 1982, "Research on Water Hammer Pump (1st Rep. Mathematical Model on Water Hammer Pump)," Turbomachinery, Vol. 10, No. 6, pp. 323-334.
- [7] Saito, Sumio, Nagata, Yoshimi, Takahashi, Masaaki, Inoue, Daijiro, and Hoshino, Yuki, "Relationship between the Basic Geometric Form and Hydraulic Characteristics of Water Hammer Pump," Transactions of the Japan Society of Mechanical Engineers, Series B, Vol. 76, No. 767, 2010-7, pp. 1028-1034.
- [8] Takahashi, Masaaki, Nagata, Yoshimi, and Saito, Sumio, "Effects of on Geometric Form Factors on Water Hammer Pump Performance," Japan Society of Mechanical Engineers Kanto Branch: the 49th student member graduation research conference, No. 902, 2010-3, pp. 301-302.