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Original Paper

Effects of the Lift Valve Opening Area on Water Hammer Pump Performance and Flow Behavior in the Valve Chamber

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Abstract

Water hammer pumps can effectively use the water hammer phenomenon for water pumping. They are capable of providing an effective fluid transport method in regions without a well-developed social infrastructure. The results of experiments examining the effect of the geometric form of water hammer pumps by considering their major dimensions have been reported. However, these conventional studies have not fully evaluated pump performance in terms of pump head and flow rate, common measures of pump performance. The authors have focused on the effects on the pump performance of various geometric form factors in water hammer pumps. The previous study examined how the hydrodynamic characteristics was affected by the inner diameter ratio of the drive and lift pipes and the angle of the drive pipe, basic form factors of water hammer pumps. The previous papers also showed that the behavior of water hammer pump operation could be divided into four characteristic phases. The behavior of temporal changes in valve chamber and air chamber pressures according to the air volume in the air chamber located downstream of the lift valve was also clarified in connection with changes in water hammer pump performance. In addition, the effects on water hammer pump performance of the length of the spring attached to the drain valve and the drain pipe angle, form factors around the drain valve, were examined experimentally. This study focuses on the form of the lift valve, a major component of water hammer pumps, and examines the effects of the size of the lift valve opening area on water hammer pump performance. It also clarifies the behavior of flow in the valve chamber during water hammer pump operation.

Keywords: Water Hammer Pump, Fluid Transients, Pump Performance, Pressure Fluctuation, Lift Valve Opening Area

1. Introduction

Water hammer pumps, taking advantage of the water hammer effect that can cause problems in fluid pipeline networks, are capable of pumping water without any outside power source; therefore, the pumps can provide an effective means of fluid transportation even in regions where social infrastructure has not yet been well developed.

There are prior studies on water hammer pumps, including proposals for their configurations, mainly for educational purposes [1], [2], [3]; for experimental results to examine the effects of major geometrical factors of the pumps [4], [5]; and a paper comparing experimental results with numerical analyses of the water hammer effect using characteristic curve method [6]. These studies, however, have not fully investigated the relationship between pump head and flow rate.

The authors have focused attention on the geometrical form factors affecting water hammer pump performance, and in the previous studies [7], [8], as the first step in evaluating the water hammer pump performance through comparison with typical turbo pump characteristics, examined how two of the basic form factors, the inner diameter ratio of the drive and the lift pipes and the drive pipe tilt angle, affected the hydrodynamic characteristics. The papers also showed that the behavior of water hammer pump operation could be divided into four characteristic phases.

The previous studies also clarified, by observing the temporal pressure changes in the valve and air chambers, that the pump characteristics are dependent upon air volume in the air chamber located downstream of the lift valve [9], [10].

Another study examined experimentally how the length of the spring attached to the drain valve and the drain pipe tilt, among the form factors around the drain valve, affect the pump performance [11].

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This study focuses on configurations of the lift valve, which is another major component of a water hammer pump, and specifically investigates how the size of the lift valve seat opening area affects the pump performance, and, at the same time, clarifies flow behaviors in the valve chamber during the pump operation.

2. Experimental Apparatus and Methods

2.1 Experimental Apparatus

Figure 1 shows an overall schematic diagram of the water hammer pump, which is the same as the one used in the experiments in the previous studies [9] – [11]. Figure 2 is a detailed diagram of the valve chamber assembly, including the lift valve. The chart includes a photo of two types of lift valve seats as examples of valve seat types.

The pump is composed of the parts ranging from the water tank ① to the drain pipe ⑨. The drive pipe ②, the valve chamber ③, and the spherical air chamber ⑥ are made of acrylic resin. The drive pipe ② is to supply water from the water tank ① to the valve chamber ③. The valve chamber ③ has a seat on its wall, on which an electro-magnetic flow velocity meter can be attached.

One of the three springs, designated as "2/3" (ℓ_s = 46.7 [mm]) in the previous study [11] is used for the spring ⑧, located downstream of the drain valve ④, to assist in opening the drain valve. The drain pipe tilt angle is set at θ_d = 0 [°].

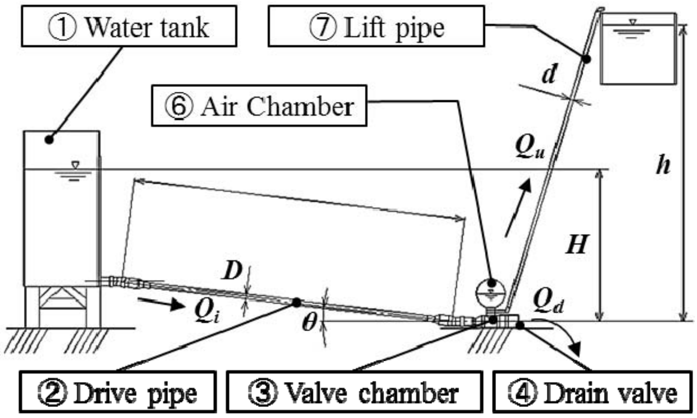


Fig. 1 Water hammer pump system

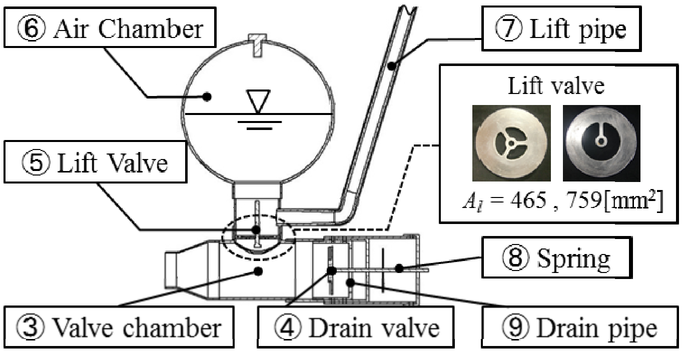


Fig. 2 Main parts of water hammer pump

2.2 The Experiment Conditions and the Geometric Form Factors

Table 1 shows the factors that will affect the hydrodynamic characteristics of the water hammer pump.

Table 1 Experimental factors of water hammer pump

Geometrical form factor			Experimental condition
Drive pipe	Inner diameter	D [mmφ]	25
	Length	L [m]	4
	Angle	θ [°]	7
Drain pipe	Angle	θ_d [°]	0
Lift valve	Valve seat opening area	A_l [mm^2]	254 , 465 , 683 , 759
Air chamber	Capacity	V [ℓ]	3.85 (Spherical type)
	Air quantity	V_a [ℓ]	1.94
Lift pipe	Inner diameter	d [mmφ]	18
Spring	Length	ℓ_s [mm]	46.7
	Constant	k [N/mm]	0.09
Water level		H [m]	0.5

Among the factors in Table 1, this paper experimentally examines how the valve seat opening area size of the lift valve ⑤ affects pump performance. The experiments are carried out using four lift valves with different valve seat opening areas; A_l = 254 [mm^2] as the reference, which was used in the previous studies [9] – [11]; 465, 683, and 759 [mm^2].

Other major factors for the water hammer pump experiments are set as follows: the inner diameters of drive and lift pipes are D = 25 [mmφ] and d = 18 [mmφ], respectively; the drive pipe length is set at L = 4 [m]; and its tilt is at θ = 7 [°], which is the same angle used in the previous studies [9] – [11].

Air volume in the air chamber is kept at V_a = 1.94 [ℓ], half of the air chamber capacity, based on the previous study results [9], [10].

2.3 Experimental Methods

The input flow rate Q_i into the water hammer pump is determined by measuring the filling flow rate into the water tank ① to keep the head from the water level in the water tank ① to the valve chamber ③ to be H = 0.5 [m] constant. In addition, the lift pipe outlet is set so as to provide the desired pump head h, and the outlet flow rate is measured with a gravimetric method to determine the lifted flow rate Q_u. The drain flow rate Q_d from the drain valve is also directly measured with the gravimetric method.

The performance of the water hammer pump is indicated in terms of the lifted flow rate Q_u and the pump head h, after the typical turbo pump performance indication. The pump efficiency η is calculated with the following equation taking into consideration the input and output flow rates of the water hammer pump [7] – [11].

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

To investigate the hydrodynamic behavior in the water hammer pump, temporal changes in pressure P_v in the valve chamber ③ and P_a in the air chamber ⑥ shown in Fig. 2 are measured with a pair of strain gauge pressure transducer (PGM-1KG, manufactured by Kyowa Electronic Instruments Co., Ltd.), an amplifier and an A/D converter.

Furthermore, in order to examine the flow behavior in the valve chamber, a sensor of an electro-magnetic velocity meter (VM-801H, manufactured by KENEK Corporation) capable of measuring simultaneously flow velocity v_x in the flow direction from the drive pipe and flow velocity v_y in the water lifting direction is installed vertically at the center of the valve chamber and horizontally co-axial to the center of the lift valve.

3. Results and Considerations

3.1 Effects of the Valve Seat Opening Area on Water Hammer Pump Performance

Figure 3 shows water hammer pump performance for four different valve seat opening areas of the lift valve. 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 the water hammer pump, the second and fourth quadrants indicate 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.

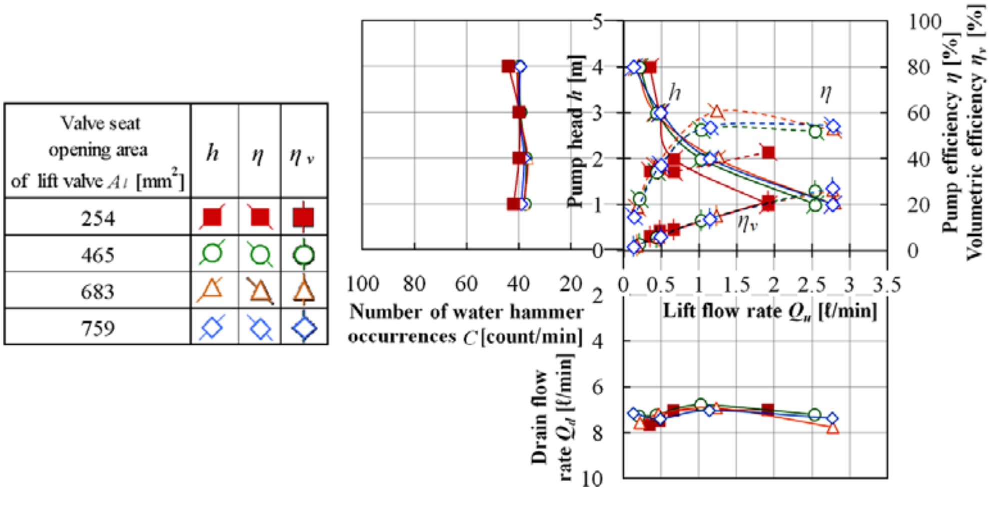


Fig. 3 Change in water hammer pump performance due to valve seat opening area of lift valve

In the first quadrant, the relationship between the pump head h and lifted flow rate Q_u is represented by downward-sloping curves, as with typical pump performance. And the curves of pump head h versus lifted flow rate Q_u show that, in a low range of the pump head, the larger the valve seat opening, the more lifted flow rate is obtained. The slope of the curves becomes smaller with increase of valve seat opening; however, in cases of $A_l = 683$ [mm^2] and 759 [mm^2], the curves become almost identical.

The results of drain flow rate Q_d versus lifted flow rate Q_u shown in the fourth quadrant indicate that Q_d is nearly constant over the whole range of Q_u regardless of valve seat opening area differences. Thus the volumetric efficiency η_v given by Eq. (1) provides nearly same curves over the whole range of the valve seat opening area, and that means the pump efficiency η is dependent on the pump head h.

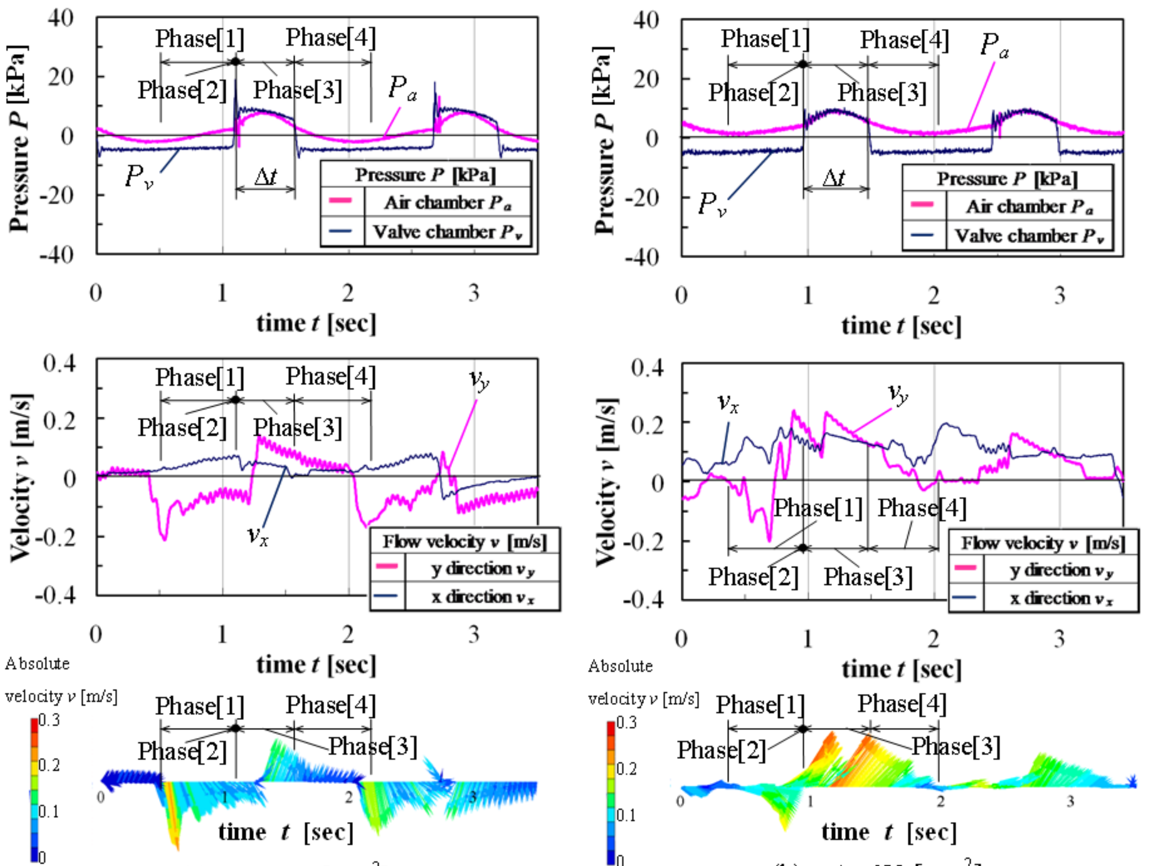
Meanwhile, the second quadrant chart shows that the number of water hammer occurrences C slightly varies with the valve seat opening area, but over the experimented range of the pump head h, C stays almost constant at approximately 40 [count/min].

3.2 Effects of the Valve Seat Opening Area on Pressure Changes in the Valve and Air Chambers and the Flow Behavior in the Valve Chamber

3.2.1 Water hammer pump behavior at pump head h = 1[m]

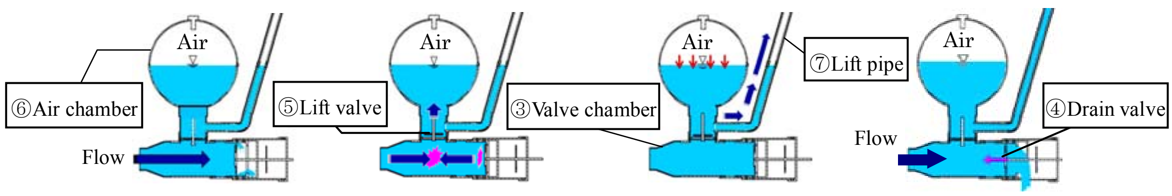
Figures 4 (a) and (b) show the results at low pump head h = 1 [m] of two lift valve seat opening area cases, A_l = 254 [mm^2] and 683 [mm^2] for temporal changes of the pressure P_v in the valve chamber and P_a in the air chamber, and also for temporal flow velocity changes in the valve chamber v_x and v_y, which are the water flow direction velocity and the water lifting direction velocity, respectively. The phases [1] to [4] shown in Fig. 4 correspond to the water hammer pump operational phases indicated in Fig. 5 [9] – [11].

For the case of lift valve seat opening area of A_l = 254 [mm^2], Fig. 4 (a) shows that, at the transition from Phase [1] to [2], the pressure in the valve chamber sharply increases; however, such instantaneous pressure increase in the air chamber is smaller than



(a) A_l=254 [mm^2] (b) A_l=683 [mm^2]

Fig. 4 Pressure fluctuations P_v , P_a and velocity fluctuations v_x, v_y, due to valve seat opening area of lift valve (h = 1 [m])



(1) Phase [1] (2) Phase [2] (3) Phase [3] (4) Phase [4]

Fig. 5 Water hammer pump operation

in the valve chamber. Phase [1], described above, is the phase water flows in the drive pipe ② from the water tank ① having the constant water level measured from the valve chamber ③ position of the water hammer pump. In Phase [2], a water hammer occurs due to quick closure of the drain valve.

During Phase [3], the time duration of which corresponds to the pressure holding time Δt, the lift valve is open, and the pressure in the valve chamber stays almost constant with only a slight decrease with time. Pressure in the air chamber becomes almost the same as that in the valve chamber in the latter half of Phase [3] duration, and varies similarly to the pressure change in the valve chamber.

In Phase [4], the lift valve closure and the drain valve opening occur almost simultaneously, and the pressure in the valve chamber decreases very rapidly, but the pressure in the air chamber slowly drops with time. Then, water flows into the valve chamber again, and thus Phase [1] to Phase [4] cycles will be repeated.

Temporal changes of two directional flows in the valve chamber are as follows: the velocity v_x of the flow from the drive pipe toward the valve chamber gradually increases in Phase [1], and then, right after Phase [2], rapidly slows down along with the quick closure of the drain valve. At the same time the lift valve opens, and the lift direction flow velocity v_y instantaneously increases.

Figure 4 (a) includes a vector representation chart of the absolute flow velocity v calculated from the flow direction velocity v_x and the lift direction velocity v_y. It shows that, in Phase [1], the flow direction is downstream towards the drain valve, and then in Phase [3] the direction changes obliquely upward, namely toward the water lift direction.

Though the temporal changes of the pressures in the valve and the air chamber are quite periodic with phase transitions from Phase [1] to [4] as described above, the flow velocity shows significantly irregular fluctuations.

Secondly, Fig. 4 (b), the case of the valve seat opening area A_l = 683 [mm^2], shows that the instantaneous pressure increase in Phase [2] is smaller than the case of A_l = 254 [mm^2]

In Phase [3], the temporal change of the pressure in the air chamber is very close to that of the valve chamber. It is because the larger opening area in the valve seat allows faster pressure propagation from the valve chamber to the air chamber.

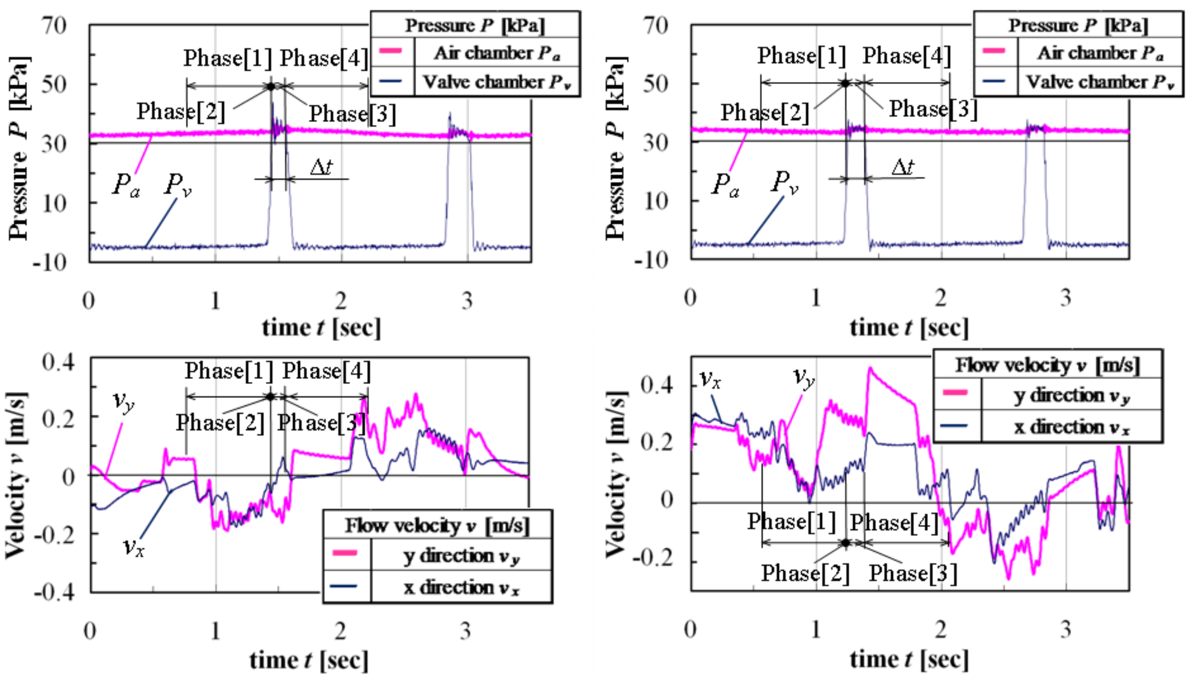
The temporal flow velocity changes in the valve chamber have certain irregular fluctuations. The detailed behaviors of the flow direction velocity v_x and the lift direction velocity v_y during each phase are different from those in the case of A_l = 254 [mm^2]. However, in Phase [2], the general trend in which v_y increases as v_x decreases is almost the same.

In case of A_l = 683 [mm^2], at the pump head h = 1 [m], the lifted flow rate is larger than that of A_l = 254 [mm^2], so that the vector direction of the absolute flow velocity changes more significantly toward lift direction in Phase [3] from the downstream flow toward the drain valve as seen in Phase [1].

3.2.2 Water hammer pump behavior at pump head *h* = 4 [m]

Figures 6 (a) and (b) are the results of the high pump head at h = 4 [m], and show the temporal changes of the pressure P_v in the valve chamber and P_a in the air chamber, and also show temporal changes of flow direction velocity v_x and lift direction velocity v_y in the valve chamber. The charts contain the results for two cases of valve seat opening area, as described in 3-2-1, A_l = 254 [mm^2] and 683 [mm^2].

Figure 6 (a), the case of the lift valve seat opening area of A_l = 254 [mm^2], shows that the pressure in the valve chamber sharply increases in Phase [2], and its peak pressure is significantly higher than that of the lower pump head at h = 1 [m].



(a) A_l=254[mm^2] (b) A_l=683[mm^2]

Fig. 6 Pressure fluctuations P_v, P_a and velocity fluctuations v_x, v_y due to valve seat opening area of lift valve (h = 4 [m])

In Phase [4], the pressure then quickly drops.

Pressure in the air chamber rapidly but only slightly increases in Phase [2], and it fluctuates also in Phase [3], but the extent of fluctuation is a little smaller than that in the valve chamber. The absolute value of the pressure in Phase [4] is slightly lower than that in Phase [3]. The temporal pressure change in the air chamber is very small throughout Phases [1] to [4].

The extent of velocity fluctuation is larger than that of h = 1 [m], and Fig. 8 (given in the next section) shows that the higher the pump head, the shorter the time for Phase [3]. These factors may contribute to the fact that the flow in the valve chamber does not show clear periodicity.

Figure 6 (b), the case of the valve seat opening area A_l = 683 [mm^2], shows that the instantaneous pressure increase in the valve chamber during Phase [2] is smaller than that of A_l = 254 [mm^2]; however, on the whole, the curve is similar to that of A_l = 254 [mm^2].

The temporal pressure change in the air chamber shows the same behavior as that of A_l = 254 [mm^2], and for the same pump head, the sizes of the valve seat opening area do not make much difference.

The temporal changes in the flow direction velocity v_x and the lift direction velocity v_y are greater than those of A_l = 254 [mm^2], and also are greater than those at lower pump head.

3.3 Effects of the Lift Valve Seat Opening Area Size on the Behavior of the Pressure Changes in the Valve and the Air Chambers

Based on the results obtained in 3.1 and 3.2, Figs. 7 and 8 illustrate how the lift valve seat opening area A_l affects the peak pressure $P_{v.peak}$ in the valve chamber and the pressure holding time Δt, respectively, with pump head h as the parameter. The upper and lower limit marks in the charts denote the extent of fluctuations of $P_{v.peak}$ and Δt over an operational cycle.

Figure 7 shows that the less the valve seat opening area A_l is, the higher peak pressure $P_{v.peak}$ reaches for each pump head. And the peak pressure $P_{v.peak}$ has a tendency to be higher when the valve seat opening area A_l is smaller, although, at lower pump heads such as h = 1 [m] and 2 [m], the peak pressure $P_{v.peak}$ is nearly the same both for A_l = 465[mm^2] and 683 [mm^2]. On the whole, over the experimented range of A_l, $P_{v.peak}$ rises with the increase of the pump head h.

Figure 8 shows that the lower the pump head is, the longer the pressure holding time Δt becomes, and that Δt stays almost the same, regardless of the valve seat opening area A_l for all pump head values.

Figure 9 shows the effect of the lift valve seat opening area A_l on the peak pressure $P_{a.peak}$ of the pressure P_a in the air chamber. The upper and lower limit marks in the charts denote the extent of fluctuations of $P_{a.peak}$ over an operational cycle.

$P_{a.peak}$ at each pump head h changes similarly to the change of the peak pressure $P_{v.peak}$ of the pressure P_v in the valve chamber shown in Fig. 7; however, $P_{a.peak}$ is generally not much affected by the size of the lift valve opening area A_l.

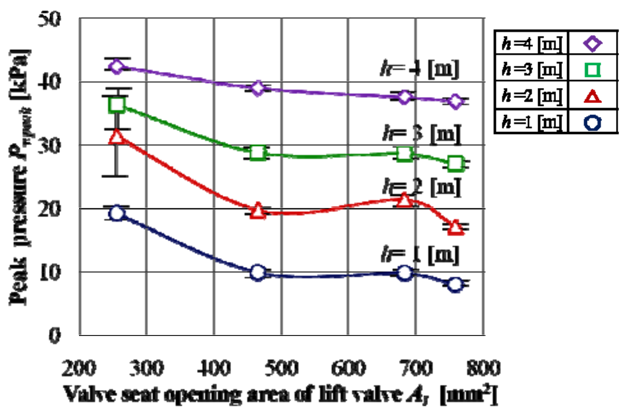


Fig. 7 Relationship between peak pressure $P_{v.peak}$ in valve chamber and valve seat opening area of lift valve

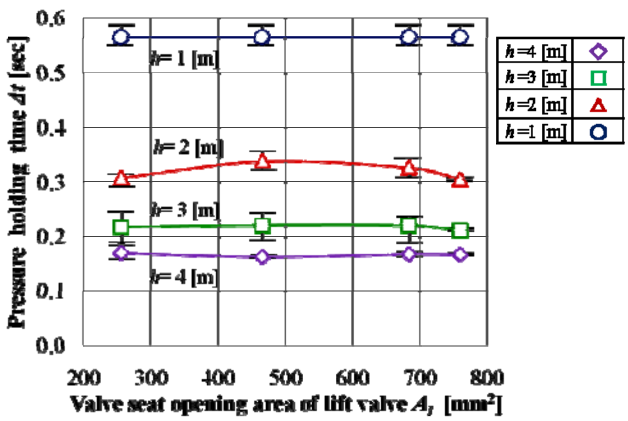


Fig. 8 Relationship between pressure holding time Δt in valve chamber and valve seat opening area of lift valve

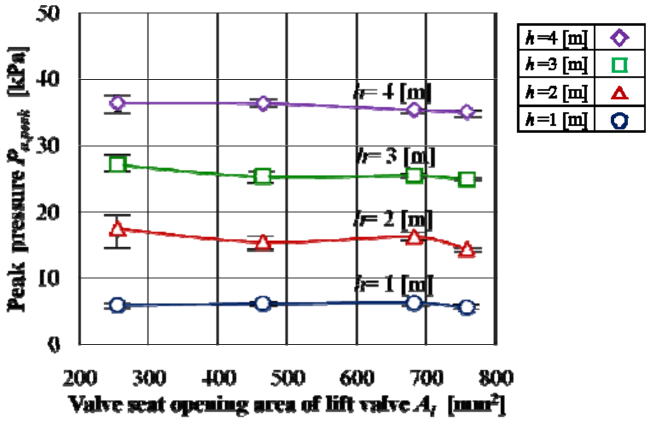


Fig. 9 Relationship between peak pressure $P_{a.peak}$ in air chamber and valve seat opening area of lift valve

4. Conclusions

In this paper, the effects of form factors of the lift valve chamber, one of the major structural components of a water hammer pump, on the pump performance have been investigated. More specifically, the effects of the lift valve seat opening area size on the pump performance have been experimentally examined. At the same time, water flow behavior in the valve chamber at each operational phase of the water hammer pump is clarified.

The following findings have been obtained as the results.

(1) With respect to the lift valve seat opening area A_l, the larger the area A_l, the less inclined becomes the slope of the pump head – lifted flow rate curves, and, at lower pump head, the curves shift in the direction of larger flow rates.

The number of water hammer occurrences C is only slightly dependent upon the size of the lift valve seat opening area, and is almost constant at 40 [count/min].

(2) Since the duration of each phase varies depending on the pump head value, the flow is not clearly periodic. Thus, the flow velocity in the valve chamber over an entire cycle of water hammer pump operation shows certain irregular fluctuations.

(3) The peak pressure $P_{v.peak}$ in the valve chamber rises with pump head increase, and the smaller the lift valve opening area A_l, the higher becomes $P_{v.peak}$ at any pump head.

The pressure holding time Δt becomes longer with lowering the pump head, and, at each pump head value, it stays almost constant regardless of the lift valve seat opening area A_l.

(4) The peak pressure $P_{a.peak}$ of the pressure P_a in the air chamber becomes higher with the increase of pump head; however, the lift valve seat opening area A_l does not much affect $P_{a.peak}$.

Nomenclature

A_l	Valve seat opening area of the lift valve [mm^2]	Q_i	Input flow rate [ℓ/min]
C	Number of water hammer occurrences [count/min]	Q_u	Lifted flow rate [ℓ/min]
D	Drive pipe inner diameter [mmφ]	ΔT	Water hammer occurrence interval [sec]
d	Lift pipe inner diameter [mmφ]	Δt	Pressure holding time during lifting operation [sec]
H	Water Level [m]		
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 tilt angle [°]
P_a	Pressure in the air chamber [kPa]	θ_d	Drain pipe tilt angle [°]
P_v	Pressure in the valve chamber [kPa]	η	Pump efficiency [%] (see Equation (1))
Q_d	Drain flow rate [ℓ/min]	η_v	Volumetric efficiency [%] (see Equation (1))
		peak (subscript)	Peak pressure

References

[1] Kagami, K., Ide, T., and Ushiyama, I., 2001, “Water hammer pump production handbook (in Japanese),” POWERSHA Inc., pp. 47.

[2] Yunoki, T., 2004, “Production of a Hydraulic Ram Pump and its Research on its Characteristic,” Japan Society for Science Education, (in Japanese), Vol. 28, No .2, pp. 94-100.

[3] Tessema, A. A., 2000, “Hydraulic Ram Pump System Design and Application,” Proceedings ESME 5th Annual Conference on Manufacturing and Process Industry, 2000-9, pp. 1-8.

[4] Hasegawa, S., Suehiro, H., and Yamaguchi, K., 1984, “Trial of Hydraulic Ram and Its Performance Characteristics,” Research Reports of Toyota College of Technology (in Japanese), No. 17, pp. 15-20.

[5] Taye, T., 1998, “Hydraulic Ram Pump,” Journal of the ESME, Vol. II, No.1 (1998-7), pp. 1-11.
[6] Okada, T, Uetsuki, H, and Takenaka, T., 1982, “Research on Water Hammer Pump (1st Rep. Mathematical Model on Water Hammer Pump),” Turbomachinery (in Japanese), Vol. 10, No. 6, pp. 323-334.
[7] Saito, et al., 2010, “Relationship between the Basic Geometric Form and Hydraulic Characteristics of Water Hammer Pump,” Transactions of the Japan Society of Mechanical Engineers, Series B, No. 09-1092 (in Japanese), Vol. 76, No.767 (2010-7), pp. 1028-1034.
[8] Saito, S., Nagata, Y., Takahashi, M., Inoue, D., Hoshino, Y., 2010, “Relationship between the Basic Geometric Form and Hydrodynamic Characteristics of Water Hammer Pump,” Journal of Fluid Science and Technology, Vol. 5, No. 3, pp. 491-502.
[9] Saito, S., Takahashi, M., and Nagata, Y., 2010, “Effects of the Air Volume in the Air Chamber on the Performance of Water Hammer Pump System,” Turbomachinery (in Japanese), Vol. 39, No. 2 (2010-2), pp. 87-94.
[10] Saito, S., Takahashi, M., Nagata, Y., 2011, “Effects of the Air Volume in the Air Chamber on the Performance of Water Hammer Pump System,” International Journal of Fluid Machinery and Systems, Vol. 4, No. 2 (April-June 2011), pp. 255-261.
[11] Saito, S., Takahashi, M., Nagata, Y., Dejima K., 2010, “Effects of the Geometry of Components Attached to the Drain Valve on the Performance of Water Hammer Pumps,” Turbomachinery (in Japanese), Vol. 39, No. 6 (2010-6), pp. 323-331.