Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 9702183, 11 pages
https://doi.org/10.1155/2019/9702183

Research Article

Determination of Hydraulic Ram Pump Performance: Experimental Results

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Received 19 September 2018; Accepted 15 November 2018; Published 4 March 2019

Academic Editor: Arnaud Perrot

The possibility of using a hydraulic ram pump (HRP) as a means of utilizing its energy to produce high head for pump has been investigated. To make such a system economically competitive, it is necessary to improve the performance of HRPs. To achieve this improvement, it is also necessary to understand the parameters that marked out the design of conventional HRPs. The performance is presented in dimensionless terms as the head ratio H^* or discharge head to drive head and flow-rate ratio Q^* or discharge flow rate to drive flow rate. The experiments on HRPs were conducted by which each of the following factors could be varied independently: (a) supply head, (b) air chamber pressure, and (c) waste valve beats per minute. An increase in the supply head tends to increase the supply flow rate, delivery flow rate, delivery head, and the overall efficiency of the pump. An increase in air chamber pressure tends to decrease the overall efficiency of the pump. However, there was no significant difference on the HRP performance over a wide range of flow conditions when air chamber pressure was varied. An increase in waste valve beats per minute tends to decrease the supply flow rate, delivery flow rate, and delivery head. But it tends to increase the head ratio, the flow-rate ratio, and the overall efficiency of the pump. The experimental data reveal that the HRP characteristics are functions of the waste valve beats per minute and the supply head.

1. Introduction

The concept of hydraulic ram pump (HRP) was developed 200 years ago. In a HRP, no external powers are required to drive water. Water is pumped from a particular head at a high flow rate and comes out with a higher head but at a lesser flow rate because of the water hammer effect. The system consists of a drive pipe, waste valve, discharge valve, air (pressure) chamber, and delivery pipe (Figure 1). The only moving parts of the system are the waste valve and the discharge valve which operate from the fluid dynamic actions of the pumping cycle [1].HRP is one of the simplest and the most environmentally friendly devices for domestic or agricultural use [2, 3]. There are a lot of people in a lot of countries that build and use this kind of pump. Details of these are given by Watt [4, 5], Schiller [6], Browne [7], and Inthachot et al. [8].

There are a number of studies which have been done to improve the design of HRPs by experimental, theoretical, and numerical approaches. A short description of the function and history of HRPs can be found in Basfeld and Miiller [9]. Experimental and theoretical investigations on HRPs were done by Lansford and Dugan [10] to determine the rate of pumping and wasting for any conditions of operation. The dominant factor controlling the functioning of the HRP is the velocity in the drive pipe necessary to cause the waste valve to start closing, and its value is fixed by the waste valve setting. They also reported that the maximum efficiency varied little with various adjustments of the waste valve, except perhaps for extremely high values of velocity in the drive pipe, at which the efficiency was somewhat lower. Details of the HRP working cycle are also described.

Iversen [1] carried out a comprehensive investigation to identify the features of the HRP; the drive head and flow, the

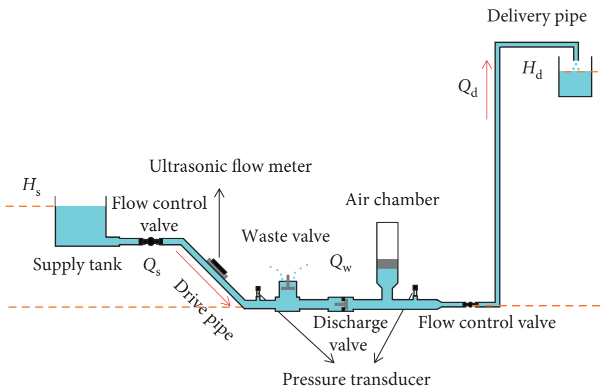

Figure 1: Schematic diagram of the HRP test facility.

discharge head and flow, the cycle frequency of the HRP, and the system efficiency. The expected performance is presented in a generalized form of the head ratio or discharge head to drive head and the flow rate ratio or discharge flow rate to drive flow rate. He reported that performance features of the head ratio and the flow rate ratio relate directly to cyclic frequency.

The method of characteristics (MOC) for the analysis of unsteady flow in a HRP system can be seen in Najm et al. [11] and Filipan et al. [12]. Filipan et al. [12] applied the MOC for the calculation of the mathematical model of a HRP system in order to obtain the simplified working cycle of the HRP. The sensitivity analysis presents the influence of the force acting on the waste valve.

CFD analysis of opening and closing condition of a hydraulic pump can be found in [13, 14] . The height of the waste valve and the height of the pressure chamber have significant effect on the outlet flow of the pump [15].

Numerous attempts to analyze the complex behavior of a HRP system have been made in the past. Many variables are involved in the operation. Investigations on the performance and its factors have been widely carried out. The available literatures aim to present a generalized design methodology for HRPs covering design parameters and the design procedure along with the mathematical relationship used for the design work. It has been found that design parameters and their effect on the performance of the HRP were not fully studied. The influence on the rate of pumping and wasting for any conditions of operation and performance in HRPs are therefore investigated in this study.

2. Pump Performance

A HRP is shown in Figure 1. The pump utilizes the energy from a supply head, H_s with a large quantity of water, Q_s to a delivery head, H_d which is higher than the supply head with a small quantity of water, Q_d by rapid closure of the waste valve. The operation is continuous with no other external input and the flow is intermittent. The power used to drive the pump is

$$\mathrm{Pow}_s = \rho g Q_s H_s. \tag{1}$$

The power added to the fluid is

$$\mathrm{Pow}_d = \rho g Q_d H_d. \tag{2}$$

The efficiency of the pump is defined as

$$\eta = \frac{\mathrm{Pow}_d}{\mathrm{Pow}_s} = \frac{\rho g Q_d H_d}{\rho g Q_s H_s} = \frac{Q_d}{Q_s} \cdot \frac{H_d}{H_s} = Q^* H^*, \tag{3}$$

where $H^* = \text{head ratio} = H_d/H_s$ and

$$Q^* = \text{flow rate ratio} = \frac{Q_d}{Q_s} \approx 1 - \frac{Q_w}{Q_s}. \tag{4}$$

We can expect that the flow-rate ratio is high by reducing water loss at the waste valve (Q_w), and the head ratio is high by increasing the momentum of the water flow in the supply pipe. For this purpose, the effect of waste valve opening and closing on pump performance is investigated in order to reduce water loss at the waste valve and increase the pumping pressure. A HRP working cycle has been relegated to Appendix.

3. Experimental Study

3.1. Apparatus. The experiment was performed in the HRP test rig (Figure 2). The pump was made of PVC pipe and fittings. The HRP has a drive pipe of a nominal pipe size of 25 mm (1 inch). The drive pipe is connected to a supply tank with a slope of 45°, as shown in Figure 2.

During the initial test, a brass check valve is used as the waste valve by mounting it in the reverse direction where the opening and closing of the valve are due to the weight of the valve disc. A brass spring check valve of size 25 mm (1 inch) is used as the discharge valve. The surge tank (or air chamber) was made of a PVC tube of size 75 mm (3 inches) with an end cap. Its total volume is 2.2 L and air volume is 1.8 L. The discharge line was made of PVC pipe of 12 mm (0.5 inch). The water flow rate was varied manually by means of a flow control valve which was installed on both the drive line and delivery line. The flow at the drive pipe Q_s was measured by an ultrasonic flow meter. The flow at the delivery pipe and that at the waste valve were collected in storage tanks during the test. The rate of delivering Q_d and wasting Q_w were determined by measuring the time required for a given quantity of water. Also, water pressure at the drive pipe and that at the delivery pipe were measured by pressure transducers. The total head at the drive or supply pipe H_s and that at the delivery pipe H_d were calculated from the measured flow rate and pressure of each pipe. The pressure at the air chamber is measured by a Bourdon-tube gauge. The motion of the waste valve was determined by filming with a video recorder. The number of valve beats each minute was counted, and then the average was computed. The specifications of the measuring devices are shown in Table 1. The uncertainty in Q_s is estimated as $\delta Q_s/Q_s = 0.02$ due to the accuracy of the measuring device. The uncertainties in Q_d and Q_w are the same and estimated as 0.05 due to the parameters used. The uncertainties in H_d and H_s are estimated as 0.025. The uncertainty of η can be calculated as $\delta\eta/\eta = 0.06$.

Figure 2: HRP test rig configuration.

Table 1: Measuring devices specifications.

Measurement	Instrument/manufacturer	Range	Accuracy (%)	Resolution
Pressure				
At the drive pipe and	Pressure transducer	0–2.5 bar	±0.25	0.0001 bar
At the delivery pipe	Seimens SITRANS P200	0–4 bar	±0.25	0.0001 bar
At the air chamber	Burdon-tube gage	0–12 bar	—	0.5 bar
Water flow rate	Ultrasonic flow meter			
At the drive pipe of flow	Seimens SITRANS FUP1010	±12 m/s	±0.5% to 2	0.1 L/min

3.2. Procedure. Before starting the pump, trapped air in the inlet to the drive pipe must be flushed out with water by opening the waste valve. The HRP will pump water to the delivery tank at most settings of the waste valve. The water flow rate can be varied quite easily by adjusting the turning of the control valve at the delivery line. However, if the control valve at the drive line is used instead, the waste valve must be adjusted, especially of valve beats for each flow rate.

In this experiment, the water level at the supply tank was kept constant while the water flow was varied. The HRP can be made to operate under different conditions by which each of the following factors could be varied independently: (a) supply head, (b) air chamber pressure, and (c) waste valve beats per minute. No test of less than five minutes was made.

3.3. Evaluation of Pump Performance

3.3.1. Supply Head. The effect of supply head on the HRP performance was studied in this case. For each supply head condition, the HRP was tuned to pump the greatest amount of water to the delivery tank at approximately the same number of waste valve beats per minute. It was found that the valve beat of 285 times/min is for $H_s = 2.5$ m and that of 282 times/min is for $H_s = 2.0$ m. The variations of the supply flow rate, Q_s, and delivery head H_d with delivery flow rate, Q_d, are shown in Figures 3 and 4, respectively. It reveals that an increase in supply head H_s, tends to increase the delivery head H_d, delivery flow rate Q_d, and supply flow rate Q_s. Therefore, we can expect higher power added to the water at a higher supply head.

Using the head ratio, H^*, and the flow rate ratio, Q^*, as parameters, the relationship of the two parameters reduces the amount of data scatter. Its head ratio, H^*, decreases with the flow rate ratio, Q^* (Figure 5). At high Q^*, the value of H^* decreases rapidly. A high H^* (in this study $H^* > 1$) means that H_d is increased, and a high Q^* (in this study $Q^* < 1$) means that water loss Q_w is decreased. This curve shows that a HRP can pump high flow for low lift, but as the lift increases, the flow decreases.

Figure 6 illustrates the HRP efficiency for the two different supply heads. The result shows that its efficiency reaches a peak near the maximum Q^* for each supply head. It should be noted that, when the supply head increases, the velocity and momentum of water in the drive pipe also increases. The result shows that the increase in the supply head increase the pump flow rate, Q_d, waste valve beats per minute, delivery power, and pump efficiency. Therefore, we must then try to make the supply head as large as possible. However, if the supply head is high and the drive pipe is long, the momentum of water in the drive pipe will be very high and the pump will be damaged. In this case, a large air chamber and air volume may be necessary to absorb the increased water hammer pressure that will occur in the HRP.

3.3.2. Air Chamber Pressure. The effect of air chamber pressure on the HRP performance was studied by replacing the PVC pipe with a pressure diaphragm tank as shown in Figure 7. In this study, the pressure values inside the air chamber were as follows: 1, 2, and 3 bar for collecting data. During the three experiments, except the pressure inside the

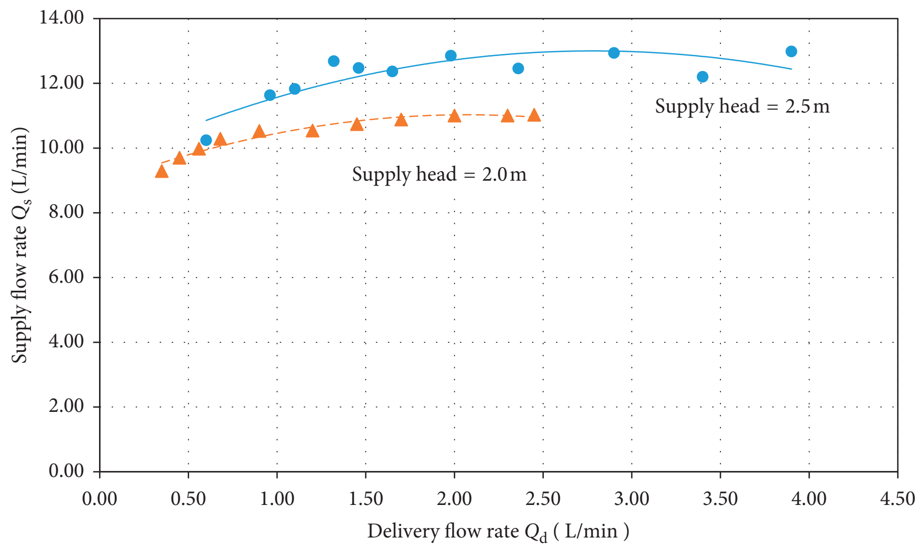

Figure 3: Supply flow rate vs. delivery flow rate at difference head, $h_s = 2.0$ and 2.5 m.

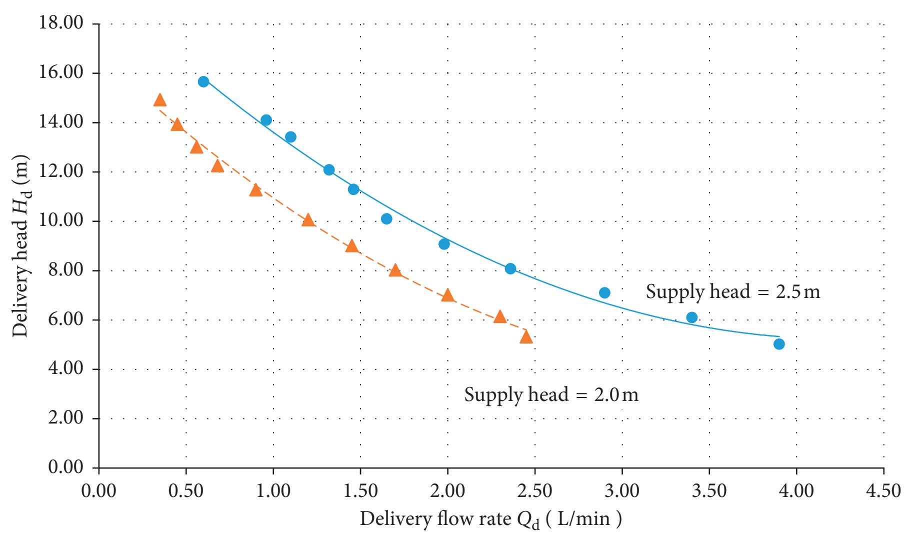

Figure 4: Delivery head vs. delivery flow rate at difference head, $h_s = 2.0$ and 2.5 m.

diaphragm tank, all other design/operational parameters are kept at their designed level. The experiment was performed at $H_s = 2.5$ m and the waste valve beat of 260 times/min.

Figures 8 and 9 illustrate the variations of the head ratio and efficiency as a function of the flow-rate ratio at different pressures inside the air chamber, $P_c = 1$, 2, and 3 bar. As seen from the figures, an increase in air chamber pressure tends to decrease the overall efficiency of the pump. However, there was no significant difference on the HRP performance over a wide range of flow conditions. The main function of the air chamber is to absorb the water hammer pressure that will occur in the HRP. Water continues to flow into the air chamber until the unbalanced force caused by the difference between supply and delivery pressures reduces the velocity to zero. The kinetic energy after the water hammer is gradually transferred to potential energy by compression of the air in the chamber and then transferred to water in the ascending pipe by expanding the volume of air. Water can thus be pumped to a considerable height by periodically opening and closing the waste valve. The pressure in the air chamber is the delivery pressure. Due to the low compressibility of water, if little or no air is present in the chamber, the energy is immediately transferred to the entire ascending pipe system, and the air chamber may burst. Therefore, in practice, adjust air pressure in the chamber so that pulse in the pipe is at a minimum. The pressure is then used to lift water to a point higher than where the water originally started with the least energy expenditure.

3.3.3. Waste Valve Beats per Minute. The effect of waste valve beats on the HRP performance was studied by replaced the check valve with a simple weighted impulse valve as shown in Figure 10. The waste valve beat was determined by

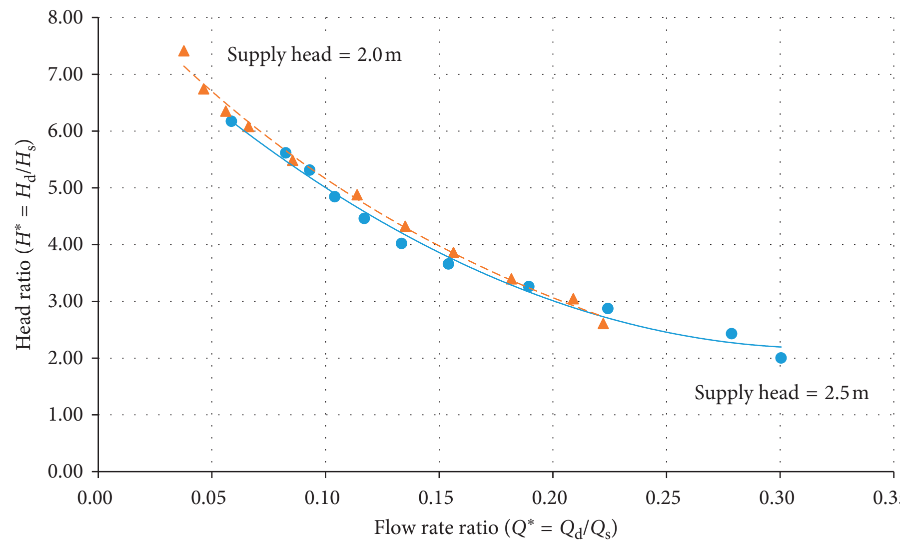

Figure 5: Head ratio vs. flow-rate ratio at difference head, $h_s = 2.0$ and 2.5 m.

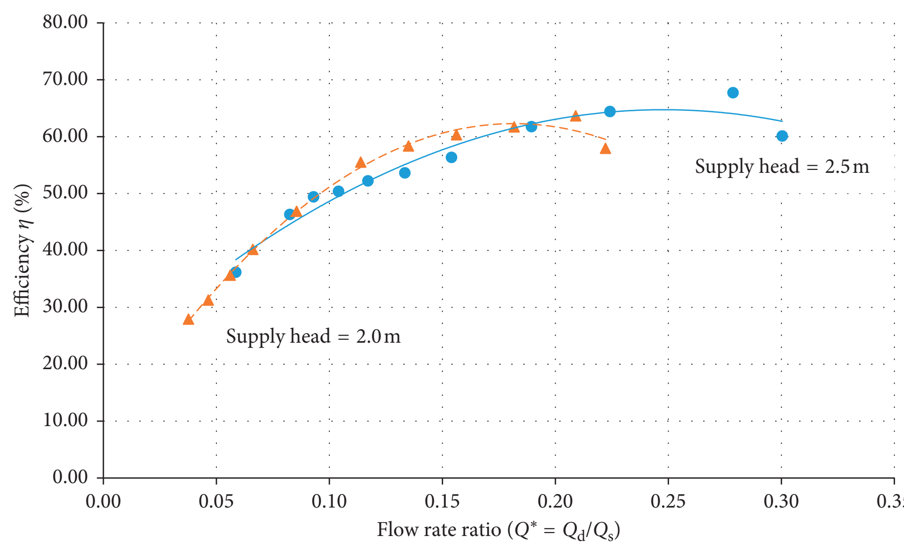

Figure 6: Efficiency vs. flow-rate ratio at difference head, $h_s = 2.0$ and 2.5 m.

adjusting the dead weight on the valve stem. With the waste valve opening area kept constant, adding weights to the valve will allow a high flow rate through the waste valve and will reduce its number of valve beats each minute. This means that the waste valve's motion in opening and closing will reduce. Taking into account the principle of the water hammer effect, a phenomenon occurs when the flowing water is suddenly brought to rest by closing the waste valve which results in a sudden increase in pressure in the pipe.

The variations of the supply flow rate, Q_s, with delivery flow rate, Q_d, are shown in Figure 11. It may be seen that an increase of waste valve beating decreases both flow rates. Figure 12 illustrates the variations of the delivery head H_d with a delivery flow rate for different valve beatings. The delivery head seems to decrease when valve beats per minute was increased. However, there was not much difference over a wide range of flow conditions when waste valve beats per minute was varied. It should be noted that with an increase in waste valve beats per minute, the time required to close the waste valve decreases. Thus, an increase of waste valve beats per minute decreases the quantity wasted per cycle. Figures 13 and 14 illustrate the variations of the head ratio and efficiency as a function of the flow ratio at different valve beats per minute, $f_b = 208$, 244, and 285 times/min. The results from this study show that an increase of waste valve beats per minute will increase H^*, Q^*, and pump efficiency.

Figure 7: HRP body with diaphragm tank.

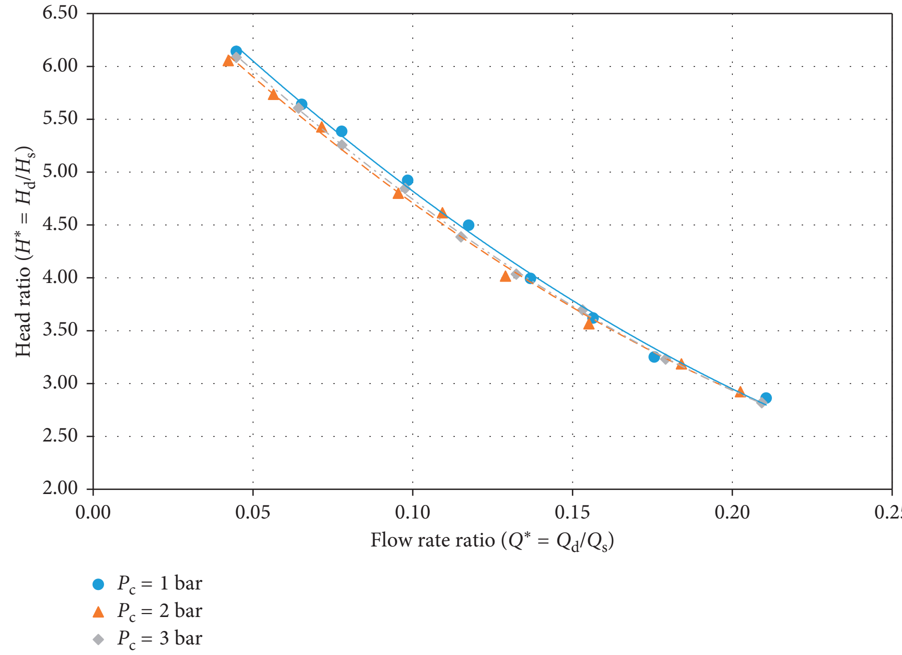

Figure 8: Head ratio vs. flow-rate ratio at the pressure difference pressure inside the air chamber, $P_c = 1$, 2, and 3 bar.

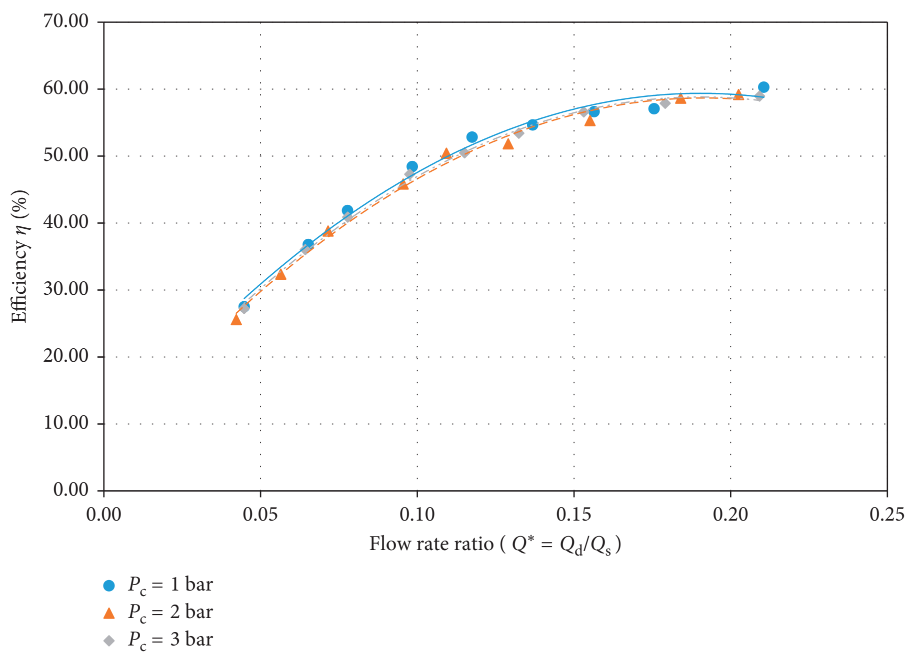

Figure 9: Efficiency vs. flow-rate ratio at difference pressure inside the air chamber, $P_c = 1$, 2, and 3 bar.

Therefore, we must then try to make the waste valve beating as fast as possible. However, if the waste valve beating is too high, there will be no build up of the powerful hammer pulse, and the flow through the waste valve is stopped.

4. Summary and Conclusions

The influence of any conditions of operation and performance on the rate of pumping and wasting in a HRP has been investigated in this study. The experiments on a HRP were conducted by which each of the following factors could be varied independently: (a) supply head, (b) air chamber pressure, and (c) waste valve beats per minute. Performance curves for variation of the head ratio, flow rate ratio, and pump efficiency at each condition have been determined.

It may be seen that the supply flow rate Q_s, the delivery flow rate Q_d, the delivery head H_d, and the pump efficiency η increase with increasing the supply head H_s. Using H^* and Q^* as parameters, the performance curves facilitated an understanding of its operation. Though the points are

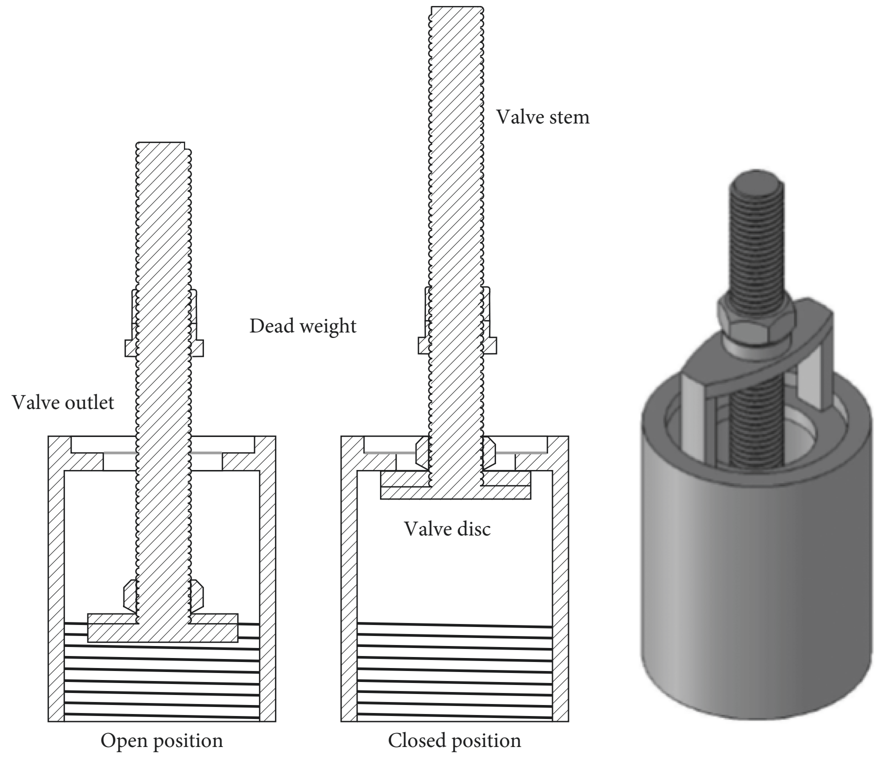

Figure 10: Drawings of a modified waste valve.

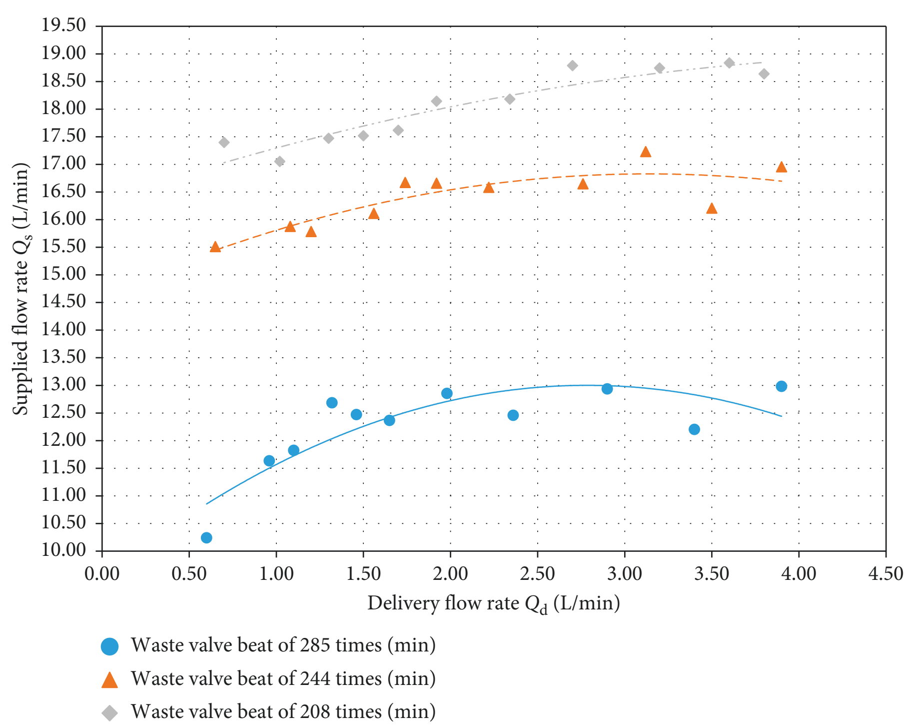

Figure 11: Supply flow rate vs. delivery flow rate at different waste valve beat rates, $f_b = 208$, 244, and 285 times/min.

somewhat scattered, it can be seen that the flow-rate ratio at which the maximum efficiency occurs becomes higher as the supply head increases. It is also apparent that an increase in the supply head, decreases water loss at the waste valve (Q_w).

Under the action of the supply head, H_s, the water in the drive line is accelerated. As the flow velocity increases, the disc of the waste valve rises due to the drag of the plate. The closure will be very rapid.

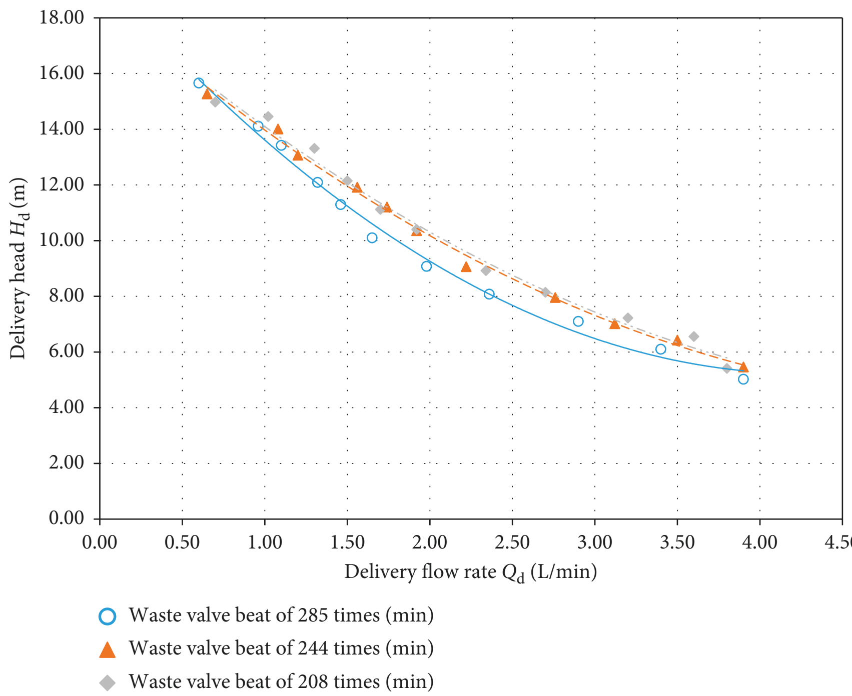

Figure 12: Delivery head vs. delivery flow rate at different waste valve beat rates, $f_b = 208$, 244 and 285 times/min.

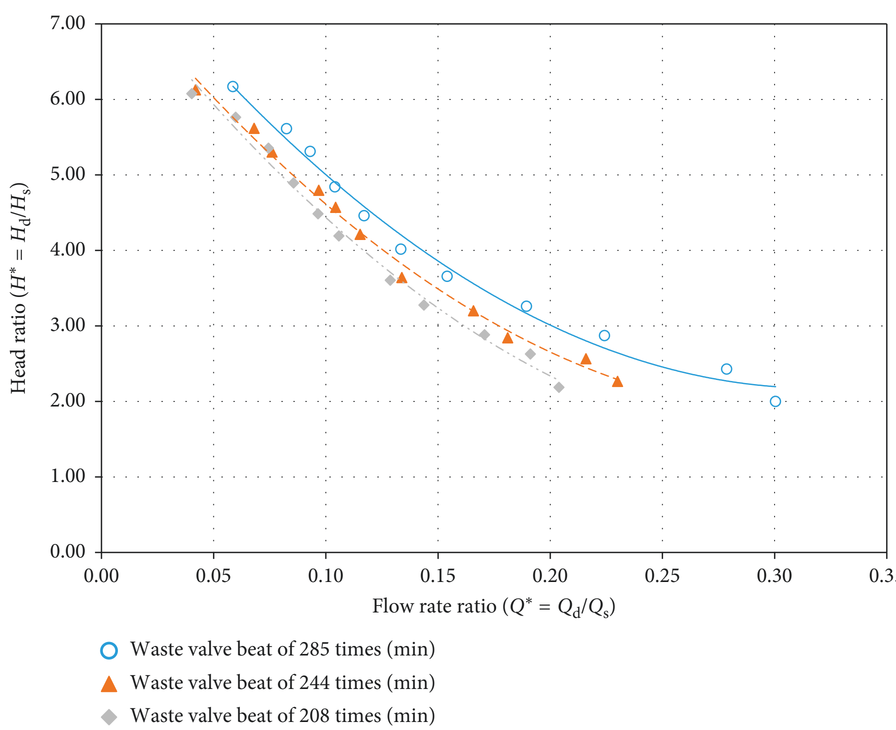

Figure 13: Head ratio vs. flow-rate ratio at different waste valve beat rates, $f_b = 208$, 244 and 285 times/min.

However, there was no significant difference on the HRP performance over a wide range of flow conditions when air chamber pressure was varied.

An increase in waste valve beats per minute tends to decrease the supply flow rate, delivery flow rate, and delivery head. But it tends to increase the head ratio, the flow-rate ratio, and the overall efficiency of the pump. It must be pointed out that there is only a limited range of waste valve beating values for each particular HRP system.

The dominant factors controlling the functioning of the HRP are the waste valve beats per minute and the supply head. A good waste valve design and proper adjustment are

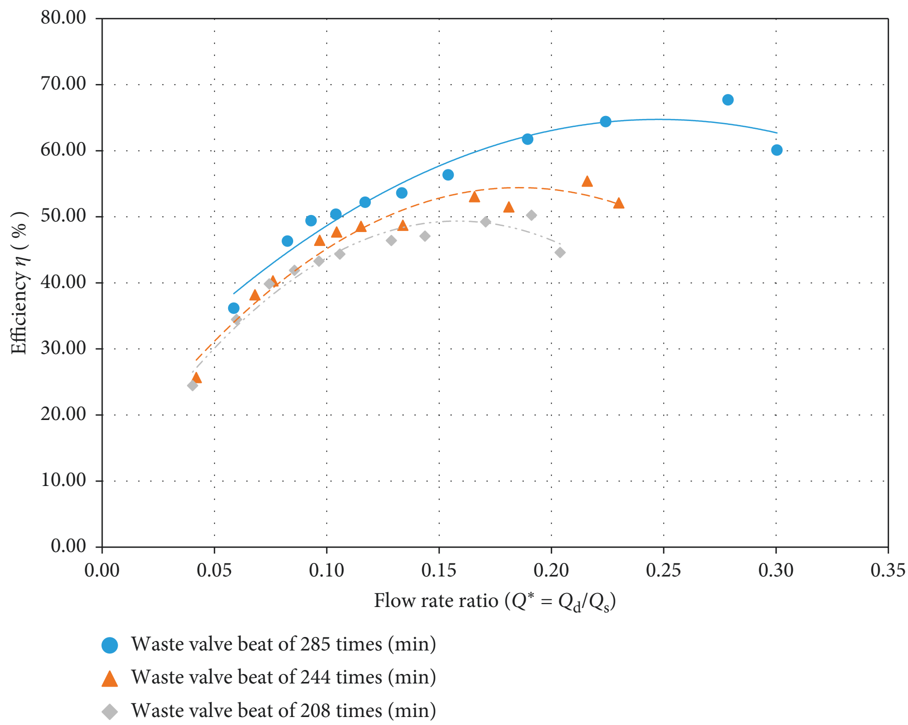

FIGURE 14: Efficiency vs. flow-rate ratio at different waste valve beat rates, $f_b = 208$, 244, and 285 times/min.

very essential for smooth and efficient HRP operation. For a given supply head, the HRP is tuned to pump the greatest amount of water possible, and this normally occurs when the waste valve beats per minute value is maximum. A more detailed analysis of the specific applications and the corresponding economic factors would be necessary to identify completely the relative merits of a HRP. Furthermore, work is in progress to study the technical feasibility for increasing lift of a conventional pump using a HRP.

Appendix

The HRP working cycle is as follows.

The process begins when water enters the drive pipe from a specific elevation height at a high flow rate. The discharge valve is a simple nonreturn valve. The discharge valve is closed, and the waste valve or impulse valve is fully opened. Water flows out around the waste valve disc. This is a wasting period since water is wasted (Figure 15). Under the action of the supply head, H_s, the water in the drive line is accelerated. As the flow velocity increases, the disc of the waste valve rises since the drag of the plate overcomes the weight of the valve.

The waste valve will close at some flow velocity. The closure will be very rapid. Thus, the flow through the waste valve is stopped, but since the water in the drive pipe has a considerable velocity, a very high pressure wave will be created. This pressure is larger than the static supply pressure. This pressure opens the discharge valve, which permits the flow of the water to continue by passing into the surge tank or air chamber. This tank is filled partly with water and partly with air. Water continues to flow into the surge tank against the pressure which exists there with decreasing

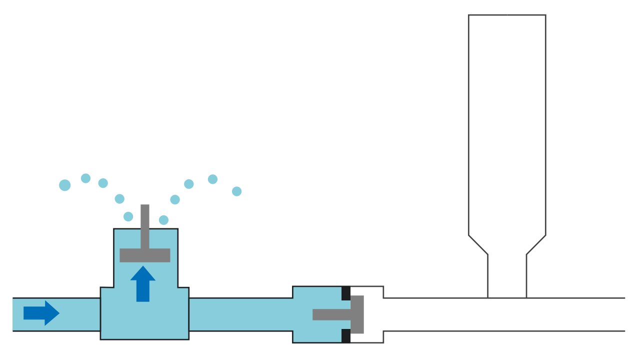

FIGURE 15: HRP working cycle: a wasting period.

velocity. There is also some energy stored in the surge tank due to air compression. The inertia of the flowing mass of fluid in the drive line maintains the flow. During this interval, the flow in the drive line is decelerated. The waste valve is closed and the discharge valve is opened. This is a pumping period (Figure 16).

When the velocity reduces to zero, the discharge pressure reverses the flow through the discharge valve and also in the drive line. The discharge valve then closes and the waste valve opens. The pressure inside the waste valve, the atmospheric pressure, and the weight of the waste valve produce a net force to open the waste valve automatically. This is a recoil period [12] (Figure 17).

When the waste valve opens, the pressure in the valve is atmospheric. Under the action of the supply head, H_s, the back flow, toward the supply reservoir, is decelerated to zero velocity and then accelerated toward the waste valve for the start of another cycle (Figure 18).

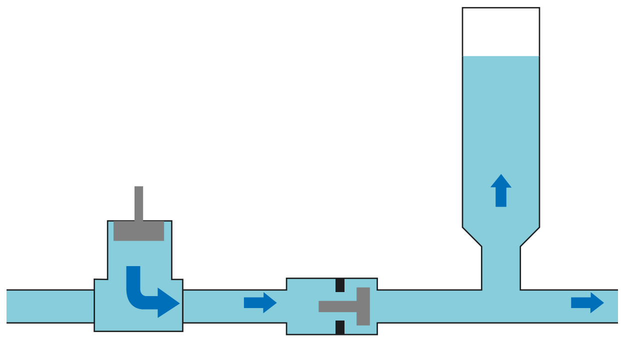

Figure 16: HRP working cycle: a pumping period.

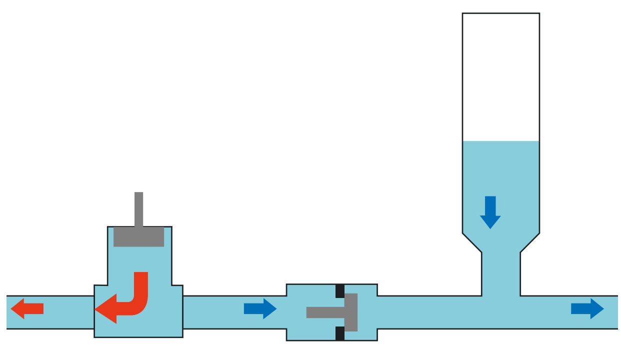

Figure 17: HRP working cycle: a recoil period.

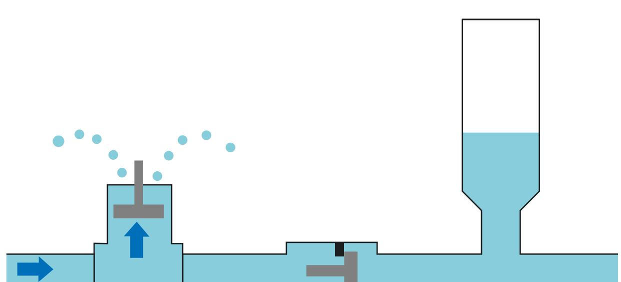

Figure 18: The automatic HRP working cycle.

Nomenclature

f_b: Waste valve beats per minute (times/min)
g: Gravitational acceleration (m/s^2)
H: Total head, m of water
HRP: Hydraulic ram pump
H^*: Head ratio
P_c: Pressure inside the air chamber (bar)
Pow: Power (W)
Q: Volume flow rate (m^3/s)
Q*: Flow-rate ratio

Greek Symbols

η: Efficiency
ρ: Density (kg/m^3)

Subscripts

d: Delivery pipe
s: Supply or drive pipe
w: Waste valve or impulse valve.

Data Availability

The Microsoft Excel Worksheet data used to support the findings of this study are available from the corresponding author upon request.

Additional Points

(i) The experiments on HRP were conducted to determine its operation and performance. (ii) Supply head, air chamber pressure, and waste valve beat rate were considered. (iii) Increase in the supply head will increase the flow rate, delivery head, and efficiency. (iv) Air chamber pressure was not a significant effect on the HRP performance. (v) Increase in the waste valve beat rate will increase the head ratio, flow-rate ratio, and efficiency. (vi) The HRP characteristics are functions of the waste valve beat rate and the supply head.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This research has been supported by the King Mongkut's University of Technology Thonburi.

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