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Development of a Testing Rig for the Ram Pump

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ABSTRACT

A testing rig for a hydraulic ram pump (HRP) is crucial as it allows for the precise assessment of pump performance, identification of potential issues, and optimization of design for maximum efficiency and reliability. This study aims to develop a testing rig for HRP and evaluate the technical performance of an HRP prototype using a three-factor factorial experiment in a completely randomized design (CRD) with drive pipe angle, waste valve angle and output pipe sizes as the factors having 27 treatments with three replications each. A testing rig was designed and constructed. It consists of a testing rig frame, water supply tank, water header tank, drive pipe, hydraulic ram pump assembly, and hydraulic ram pump support assembly. The rig was used in the evaluation of an HRP prototype. Results showed that at a combination of 10° drive pipe angle, 34° waste valve angle, and 1.0″[A1] diameter output pipe, the highest mean HRP volumetric efficiency of 92.46 % was obtained with mean output discharge of 6.446 L/min, mean pressure of 55.16 kPa and mean water delivery head/height of 6.31 m. The highest mean output discharge of 15.440 L/min was obtained at treatment combinations of 10° drive pipe angle, 46° waste valve angle and 1.0″ diameter output pipe with mean HRP volumetric efficiency of 55.17%, mean pressure of 62.05 kPa and mean water delivery head of 6.34 m. The highest mean pressure of 68.95 kPa was obtained at the treatment combination of 10° drive pipe angle, 46° waste valve angle, and 0.5″ and 0.75″ diameter output pipes. The developed testing rig for a hydraulic ram pump would help ensure optimal performance, reliability, and efficiency by enabling precise assessment and issue identification.

Keywords: Design and development, hydraulic ram pump, technical performance, testing rig

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INTRODUCTION

Effective irrigation and efficient water use are crucial factors in achieving good

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productivity, profitability, and high economic quality of the agriculture industry. In developing countries, water resources are predominantly rationed and used up in agriculture, particularly irrigation. In the Philippines, irrigation research and development are primarily directed towards large or small-scale pumps and tube well irrigation systems for rice production. There are still limited advancements in farmer-led irrigation development, small-scale irrigation systems, and technologies supporting farming systems in the elevated farmlands of the country. This is contrary to the context that most water resources, such as springs, small-scale diversion dams, micro-irrigation systems, and irrigation distribution systems, such as drip and sprinkler irrigation, are starting to gain traction as an initiative by local farmer groups in highland vegetable farming systems (Sheikh et al., 2014).

Hydraulic Ram Pump

Hydraulic ram pump (HRP) is one of the renewable energy technologies. It has been used to provide water needed for irrigation and domestic purposes, particularly in areas with limited water resources. This mechanical hydro-power device is well established for domestic and farm water pumping at remote sites, with a steady water flow at a low level. The momentum of the stream flow is used to pump some of the water from lower to higher elevations. Due to technological advancement, most technologies rely on sources of power derived from fossil fuels, thus neglecting the HRP (Nederstigt, 2014). Over the last two centuries, the designs of HRP have been stabilized, and many variations of the basic configuration (drive pipe, pump, pump house, and delivery pipe) have been tried. It is clearly a useful way of filling a header tank for piped water, especially in rural areas (Twidell & Weir, 2006). With many HRP designs, it is difficult to establish which is the most efficient and effective. Water flow rate, pipe size, elevations, and ram pump designs are the basic factors that affect the pumping rate of the HRP. This study aims to test and evaluate the efficiency of an HRP prototype to guide users, technologists, and developers interested in using ram pumps for economic development. The study's general objective is to develop a testing rig for HRP. Specifically, this study aims to (1) design and fabricate a testing rig for HRPs and (2) evaluate the performance of an HRP prototype using the testing rig in terms of water output discharge, pressure build-up in the air chamber, height of water discharge/delivery head, and volumetric efficiency as affected by the drive pipe angle, waste valve angle, and output pipe sizes.

METHODOLOGY

Basic Components of the Testing Rig for HRP

The testing rig for HRP is intended to provide a facility in the College of Engineering that could evaluate the technical performance of any HRP under different conditions, including but not limited to the volume of the water source, elevation of the water header source, size of the drive pipe, angle of inclination of the delivery pipe, design of the HRP, and size of the delivery pipe, among others. The testing rig comprises seven major parts: the water supply tank, testing rig frame, water header tank, drive pipe (input pipe), HRP assembly, HRP support assembly, and the water delivery pipe (output pipe). Figure 1 shows the proposed testing rig with its components.

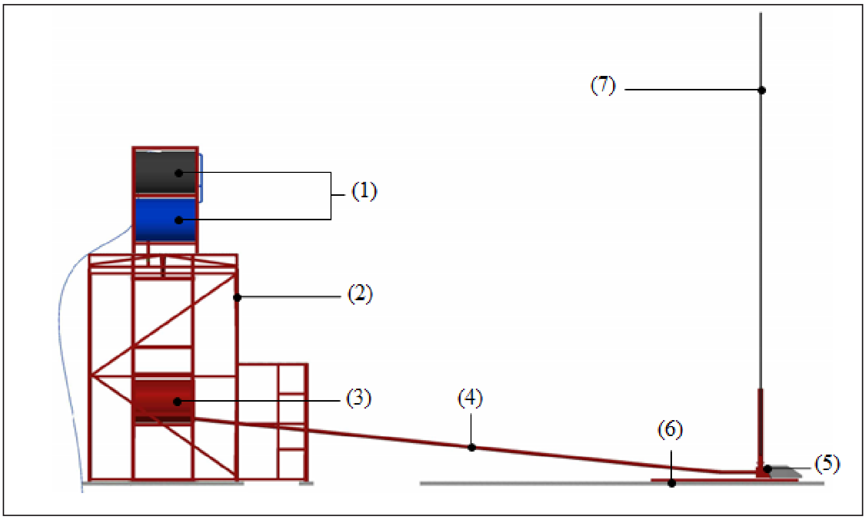

Figure 1. The proposed testing rig for the hydraulic ram pump showing the water supply tank (1), testing rig frame (2), water header tank (3), drive pipe (4), hydraulic ram pump assembly (5), ram pump support assembly (6), and the water delivery pipe (7)

Design and Fabrication of Different Components of the Testing Rig

Testing Rig Frame

The testing rig frame is mainly composed of two parts: the support for the water supply tank and the support for the water header tank. The design of these two main parts of the testing rig frame and the materials used in their fabrication are described below.

Water Supply Tank Support. The water supply tank is constructed on a plain concrete foundation with four main pillars. The pillars are 5.10-cm (2″) diameter G.I. pipe 3.1-m (122″) high and supported by welded 5.10-cm (2″) angle bars. A 16-mm diameter plain round bar flooring is constructed at the top of the pillars.

Water Header Tank Support. The water header tank support is constructed within the pillars. The support is vertically welded and made of 5.10-cm (2″) angle bars forming a rectangular shape. The water header tank can be adjusted to any elevation through a frame of 5.10-cm (2″) angle bars. The support and the frame are pinned through a 16-mm hole with a 16-mm diameter plain round bar.

Water Supply Tank

The water supply tank is made of two petrol oil barrels that can hold approximately 232 liters of water each. One barrel is placed atop the other with the required metal support of 5.10 cm (2″) angle bars. The top barrel receives water supplied by a 1.27-cm (0.5″) diameter water-blue pipe connected to a constant source through a 2.54-cm (1.0″) diameter hole bored on the top side of the barrel. At the bottom of the top barrel is a hole of 0.5-in in diameter welded to a 0.75-in G.I. pipe that channels the water directly to the second barrel. Like the top barrel, the water header tank is the water that receives water supplied by a 5.10-cm (2″) diameter G.I. pipe connected on the bottom side of the second barrel. The water supplied to the water header tank is controlled by a gate valve.

Water Header Tank

The water header tank is made of one petrol oil barrel, similar to the water supply tank arrangement. The barrel is cut fully open at the top side and placed below the second barrel with the required metal support frame made of 2″ (5.10 cm) angle bars. It receives the water supplied by a 2″ (5.10 cm) diameter G.I. pipe connected from the second barrel above.

Drive Pipe

The drive pipe is directly connected at the bottom of the water header tank. It is made of 2″ (5.10 cm) diameter and 8 meters long G.I. pipe. The length of the drive pipe was computed using the formula:

$$150 < L/D < 1000$$

Using a 2″ or 5.08 cm Ø drive pipe,

$150 < L/D$	$1000 > L/D$
$150(5.08\ \text{cm}) < L$	$1000(5.08\ \text{cm}) > L$
$L > 762$ cm or 7.62 meters	$L < 5080$ cm or 50.80 meters

Thus, for a 2″ (5.10-cm) diameter G.I. pipe, a drive pipe greater than 7.62 meters and shorter than 50.80 meters should be used. It is connected to the HRP through an angled 2″ (5.10-cm) diameter G.I. pipe and G.I. union.

The Hydraulic Ram Pump Assembly

An HRP is composed of eight parts: (1) the drive pipe, (2) the HRP body, (3) the waste valve, (4) the check valve (delivery valve), (5) the air chamber, (6) snifter, (7) water delivery pipe, and (8) the wastewater catcher. The source water is directed to the pump through the drive pipe. When water enters the HRP, the waste valve closes due to pressure, which creates high pressure in the HRP body. This high pressure opens the check valve, and water rushes to the air chamber. It compresses the air inside the chamber, and the compressed air forces the water downward, causing the check valve to close. Then, water in the air chamber is diverted to the delivery pipe. The pressure in the HRP body drops and opens the waste valve, allowing water to flow outside. The cycle repeats, and the HRP operates continuously. Design considerations of different components of the HRP and the material used in their fabrication are described below.

HRP Body

The whole HRP body is made up of 1/4″ (0.635 cm) thick stainless-steel plates. It is rectangular in shape with an inclined frontal face. The walls of the HRP body are fully welded with each other, and a flange in the front is made for the waste valve. A 3″ (7.65-cm) diameter hole is made at the upper side of the HRP body, and a 5-cm long and 3″ (7.65-cm) diameter G.I. pipe is connected and welded fully. A flange is also connected to the upper edge of the 3″ diameter G.I. pipe.

Waste Valve

The waste valve comprises welded 1/4″ (0.635-cm) thick stainless-steel plates and is fabricated with a rectangular flange. The cross-sectional area of the waste valve opening is 24.93 cm^2. The swing valve or door is attached to a fixed fabricated door hinged to swing in an inward direction. A bolt is fitted at the middle of the swinging valve to hold the rubber gasket attached to the front side of the swing valve together with the additional weight for the swing valve. The edges of the opening, which the swing valve closes, are sealed with a rubber gasket. A stopper is made inside the HRP body to prevent the swing valve from totally opening and to adjust the opening of the swing valve. It is made up of a horizontal stainless steel welded in two 1/4″ x 2 1/2″ stainless steel bolts. It is bolted beside the opening of the waste valve for easy adjustments. The swing valve is attached to the rectangular flange, which is removable and sealed with a rubber gasket to prevent leakage. The rubber gasket and flange are fastened by 3/8″ x 1″ bolts in the HRP body. The rectangular flange will be removed when adjustments to the ram body are made.

Check Valve

The check valve is made of a 1/4″ (0.635 cm) thick circular steel plate welded at the top of the HRP body. The steel plate is bored with eight holes, each 10 mm in diameter. The total cross-sectional area of the holes is equivalent to the cross-sectional area of the drive pipe. The moving part of the check valve uses circular rubber from used car tires, adopting the design from the AIDFI and adding a washer that presses the car tire rubber, following the mechanism of Watt's design.

Air Chamber

The air chamber is made up of a 3″ (7.65 cm) diameter and 1-m long G.I. pipe. A flange is made at the end of the pipe, and eight holes are bored for bolt fitting in connecting to the HRP body. The other end of the chamber is closed by a welded steel plate. A rubber gasket is used between flanges to prevent leakage. A 1″ (2.55 cm) hole is bored outside the air chamber and connected with a G.I. nipple 3″ (7.65 cm) long. It is connected to the delivery pipe. A pressure gauge is installed at the top side of the air chamber through a bored hole connected with a 12-mm diameter pipe.

Delivery Pipe

The delivery pipe is made of a G.I. pipe. It is parallel to the air chamber and connected to the bottom side through an elbow. The elbow facilitates the water coming out of the delivery pipe.

Snifter

The snifter is a small hole less than 1 mm in the HRP body. It is bored 2 cm below the check valve on the left side of the cylinder.

Wastewater Catcher

The wastewater catcher is made of stainless steel and designed to catch wastewater coming out of the check valve.

HRP Support Assembly

The HRP support assembly is made of plain concrete. It includes a welded HRP holder that is 2.44 m long and made of 1″ (2.55 cm) angle bars and a 16-mm diameter plain round bar. The holder is fastened in the assembly to hold the ram pump.

Technical Performance Evaluation of the Fabricated HRP

A preliminary evaluation of the fabricated HRP was done to determine whether it meets the standard and considerations intended for the study. It was also a way to identify issues that still needed improvement. The final evaluation of the system was implemented after a series of improvements involving precise data gathering and analysis.

Experimental Design and Treatments

In order to achieve the objectives of the study, the technical performance of the HRP was evaluated using a three-factor-factorial experiment in a completely randomized design (CRD) with the angle of elevation of the drive pipe or drive head (H), angle of inclination of the waste valve or waste valve clearance (Θ_w) and delivery pipe size diameter (Ø) as the factors (variables). Each factor comprised three treatments, which were replicated thrice. So, there were 3x3x3 = 27 treatment combinations (T_1 – T_{27}; Table 1). Three treatments for the angles of elevation of the drive pipe used were H_1 = 5°, H_2 = 10°, and H_3 = 15°. The treatments for the angles of elevation of the drive pipe were: Θ_{w1} = 34°, Θ_{w2} = 46°, and Θ_{w3} = 59°. The treatments for delivery pipe diameter sizes were: $Ø_1$ = 1″, $Ø_2$ = 3/4″, and $Ø_3$ = ½″.

Table 1
Variables evaluated in each treatment

Treatment Combination	Variable		
	The angle of Elevation of Drive Head (H)	**Angle of Inclination of the Waste Valve (Θ_w)**	**Delivery Pipe Diameter Size (Ø)**
T_1	5°	34°	1/2″
T_2	5°	34°	3/4″
T_3	5°	34°	1″
T_4	5°	46°	1/2″
T_5	5°	46°	3/4″
T_6	5°	46°	1″
T_7	5°	59°	1/2″
T_8	5°	59°	3/4″
T_9	5°	59°	1″
T_{10}	10°	34°	1/2″
T_{11}	10°	34°	3/4″
T_{12}	10°	34°	1″
T_{13}	10°	46°	1/2″
T_{14}	10°	46°	3/4″
T_{15}	10°	46°	1″
T_{16}	10°	59°	1/2″
T_{17}	10°	59°	3/4″
T_{18}	10°	59°	1″
T_{19}	15°	34°	1/2″
T_{20}	15°	34°	3/4″
T_{21}	15°	34°	1″
T_{22}	15°	46°	1/2″
T_{23}	15°	46°	3/4″
T_{24}	15°	46°	1″
T_{25}	15°	59°	1/2″
T_{26}	15°	59°	3/4″
T_{27}	15°	59°	1″

Data Collection

Pressure

Pressure is determined by reading a pressure gauge connected to the air chamber.

Delivery Water Discharge (Q)

The water discharged by the delivery pipe is determined by a volumetric method using a bucket. An elbow is inserted at the tip of the delivery pipe to direct the flow to the bucket. The water discharge is measured in volume per unit time (liters per minute).

Height of Water in each Pump

The height of water delivered by the HRP (delivery head) through the delivery pipe for each treatment/treatment combination was determined using the same pipe without the elbow at the tip. A measuring tape was installed at the tip of the delivery pipe to determine the height of the pump.

Ram Pump Efficiency

Four variables measured in the HRP efficiency (%) computation are mentioned below.

Height of Source or Drive Head (H)

Three heights are established based on the angle of elevation of the header tank. These were measured from the waste valve to the header tank.

Height of Delivery Water Discharge or Delivery Head (h)

The height of the delivery pipe was measured from the header tank to the tip of the delivery pipe.

Waste Valve Water Discharge (Q_w)

The flow rate of the water discharged by the waste valve or the wastewater is measured using the volumetric method. The bucket was placed at the tip of the wastewater catcher to measure the wastewater. It was expressed in volume per unit time (liters per minute).

Statistical Analysis

The effect of the drive head, waste valve clearance, and the diameter of the delivery pipe on the discharge and efficiency of the pump were analyzed using analysis of variance (ANOVA) for a three-factor factorial experiment in a completely randomized design. Treatment means were compared using Tukey's Honestly Significant Difference (HSD) method whenever the null hypothesis on the equality of treatment mean was rejected at a 5% level of significance.

RESULTS AND DISCUSSION

Technical Performance of HRP

Figure 2 shows the completed and functional Testing Rig with its components. The technical performance of the HRP prototype using the Testing Rig was evaluated following a 3 x 3 x 3 factor-factorial experiment in a Completely Randomized Design (CRD) with the angle of elevation of the drive pipe, angle of inclination of the waste valve, and delivery pipe size/diameter. These three variables/factors were evaluated for their effect on the water output discharge, Q; the water height at the delivery pipes, H); and pressure developed inside the air chamber, P. The results of the technical evaluation are presented in the following sections.

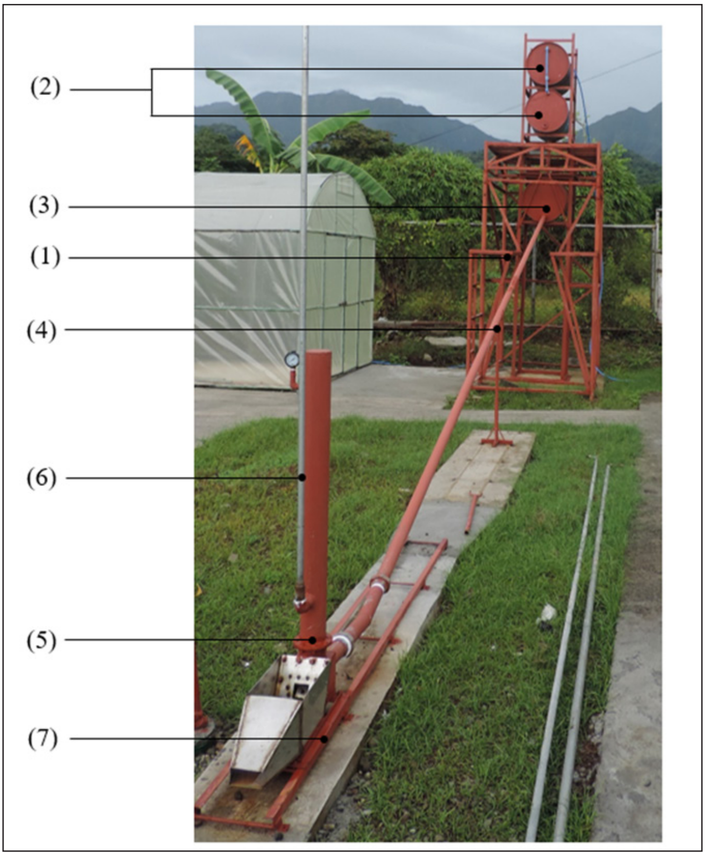

Figure 2. The components of the constructed testing rig for the hydraulic ram pump: (1) testing rig frame, (2) water supply tank, (3) water header tank, (4) drive pipe, (5) hydraulic ram pump, (6) delivery pipe, and (7) HRP support assembly

Water Output Discharge

The raw data on the water output discharge of the HRP as affected by the different factors are presented in Table 2. The HRP had the highest water output discharge when operated at T_{15} (H = 10°, Θ_w = 46°, Ø = 1″) with a mean output discharge of 15.440 L/min and lowest at T_{19} (H = 15°, Θ_w = 34°, Ø = 1/2″) with a mean output discharge of 2.101 L/min. Table 3 contains ANOVA results on the three factors affecting the water output discharge.

Table 2
Water output discharge (L/min) at each treatment combination in three replications

Treatment (H, Θ_w, Ø)	**Replication**			**Mean**
	1	**2**	**3**	
T_1 (5°, 34°, 1/2″)	0	0	0	0
T_2 (5°, 34°, 3/4″)	0	0	0	0
T_3 (5°, 34°, 1″)	0	0	0	0
T_4 (5°, 46°, 1/2″)	7.84	8.43	8.04	8.10
T_5 (5°, 46°,3/4″)	8.24	8.02	8.81	8.36
T_6 (5°,46°,1″)	7.16	8.08	7.07	7.44
T_7 (5°, 59°, 1/2″)	7.58	7.00	6.87	7.15
T_8 (5°, 59°, 3/4″)	7.40	7.05	7.18	7.21
T_9 (5°, 59°, 1″)	6.72	6.90	6.70	6.77
T_{10} (10°, 34°, 1/2″)	6.04	5.56	5.74	5.78
T_{11} (10°, 34°, 3/4″)	5.72	6.00	6.02	5.91
T_{12} (10°, 34°, 1″)	6.40	6.38	6.56	6.45
T_{13} (10°, 46°, 1/2″)	14.62	14.31	14.87	14.60
T_{14} (10°, 46°, 3/4″)	14.64	13.80	14.84	14.43
T_{15} (10°, 46°, 1″)	15.29	15.63	15.40	15.44
T_{16} (10°, 59°, 1/2″)	0	0	0	0
T_{17} (10°, 59°, 3/4″)	0	0	0	0
T_{18} (10°, 59°, 1″)	0	0	0	0
T_{19} (15°, 34°, 1/2″)	2.15	1.86	2.29	2.10
T_{20} (15°, 34°, 3/4″)	2.22	2.24	2.13	2.20
T_{21} (15°, 34°, 1″)	2.39	2.96	2.28	2.54
T_{22} (15°, 46°, 1/2″)	0	0	0	0
T_{23} (15°, 46°, 3/4″)	0	0	0	0
T_{24} (15°, 46°, 1″)	0	0	0	0
T_{25} (15°, 59°, 1/2″)	0	0	0	0
T_{26} (15°, 59°, 3/4″)	0	0	0	0
T_{27} (15°, 59°, 1″)	0	0	0	0

Note : A 0 value means the HRP is not operating
H : Drive pipe angle or angle of elevation of the drive pipe
Θ_w : Waste valve angle or angle of inclination of the waste valve
Ø : Delivery or output pipe diameter size

Table 3

Analysis of variance (ANOVA) on the water output discharge (L/min) of the hydraulic ram pump as affected by drive pipe angle, waste valve angle, and output pipe size for three replications

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Statistic Value	p-value
Drive Pipe Angle (A)	2	541.82	270.91	5044.06***	0.00
Waste Valve Angle (B)	2	458.67	229.34	4269.96***	0.00
Output Pipe Size (C)	2	0.14	0.07	1.29[ns]	0.28
A x B	4	914.03	228.51	4254.52***	0.00
A x C	4	2.53	0.63	11.79***	0.00
B x C	4	0.67	0.17	3.14*	0.02
A x B x C	8	1.18	0.15	2.74**	0.01
Error	54	2.90	0.05		
Total	80	1921.94			

ns - not significant; * - significant; ** - highly significant; *** - very highly significant

The analysis of variance indicates that the interaction among drive pipe angle, waste valve angle, and output pipe size has a highly significant effect on the water output discharge. However, the interaction effect between drive pipe angle and waste valve angle contributes the most to the differences in water output discharge, accounting for almost 48% of the total variation. Table 4 presents the results of the comparison of the treatments with nonzero water output discharge.

Table 4

Comparison of the mean water output discharge at different combinations of (A) drive pipe angle, (B) waste valve angle, and (C) output pipe size

Treatment (A,B,C)	Mean	Treatment (A,B,C)	Mean	Treatment (A,B,C)	Mean
T_{15} (10°, 46°, 1″)	15.44[a]	T_{6} (5°, 46°, 1″)	7.44[cde]	T_{11} (10°, 34°, 3/4″)	5.91[gh]
T_{13} (10°, 46°, 1/2″)	14.60[ab]	T_{8} (5°, 59°, 3/4″)	7.21[def]	T_{10} (10°, 34°, 1/2″)	5.78[h]
T_{14} (10°, 46°, 3/4″)	14.43[b]	T_{7} (5°, 59°, 1/2″)	7.15[ef]	T_{21} (15°, 34°, 1″)	2.54[i]
T_{5} (5°, 46°, 3/4″)	8.36[c]	T_{9} (5°, 59°, 1″)	6.77[efg]	T_{20} (15°, 34°, 3/4″)	2.20[i]
T_{4} (5°, 46°, 1/2″)	8.10[cd]	T_{12} (10°, 34°, 1″)	6.45[fgh]	T_{19} (15°, 34°, 1/2″)	2.10[i]

*Means with the same letters are not significantly different at the 5% level of significance using Tukey's Honestly Significant Difference (HSD) Method

Results of Tukey's test (Table 4) show that treatments T_{15}, T_{13}, and T_{14} produced output discharge of 15.44, 14.60, and 14.43 L/min, respectively. The three lowest water output discharges come from T_{21}, T_{20}, and T_{19} at 2.54, 2.20, and 2.10 L/min, respectively. The interaction effect between drive pipe angle and waste valve angle using an output pipe of 1″ diameter is compared in Figure 3. The waste valve angle of 46°, 50°, and 34° provided the highest water output discharge at the 10°, 5°, and 10° drive pipe angle, respectively. However, the 34° waste valve angle produced the same amount of water output discharge at the 15° drive pipe angle, unlike the 46° and 59° waste valve angles.

The interaction effect between the drive pipe angle and waste valve angle using an output pipe of 3/4″ diameter is presented in Figure 4. The waste valve angles of 46°, 59°, and 34° provided the highest water output discharge at 10°, 5°, and 10° drive pipe angles, respectively. However, the 34° waste valve angle produced the same amount of water output discharge at the 15° drive pipe angle, unlike the 46° and 59° waste valve angles. This result is the same as obtained with the 1″ diameter output pipe.

Figure 5 illustrates the interaction effect between the drive pipe angle and waste valve angle using an output pipe of 1/2″ diameter. Again, the 46° waste valve angle delivered the highest water output discharge at the 10° drive pipe angle, similar to its behavior in the larger diameters. The 59° and 34° waste valve angles also remained consistent in their water output discharge at the different angles of elevation of the drive pipe.

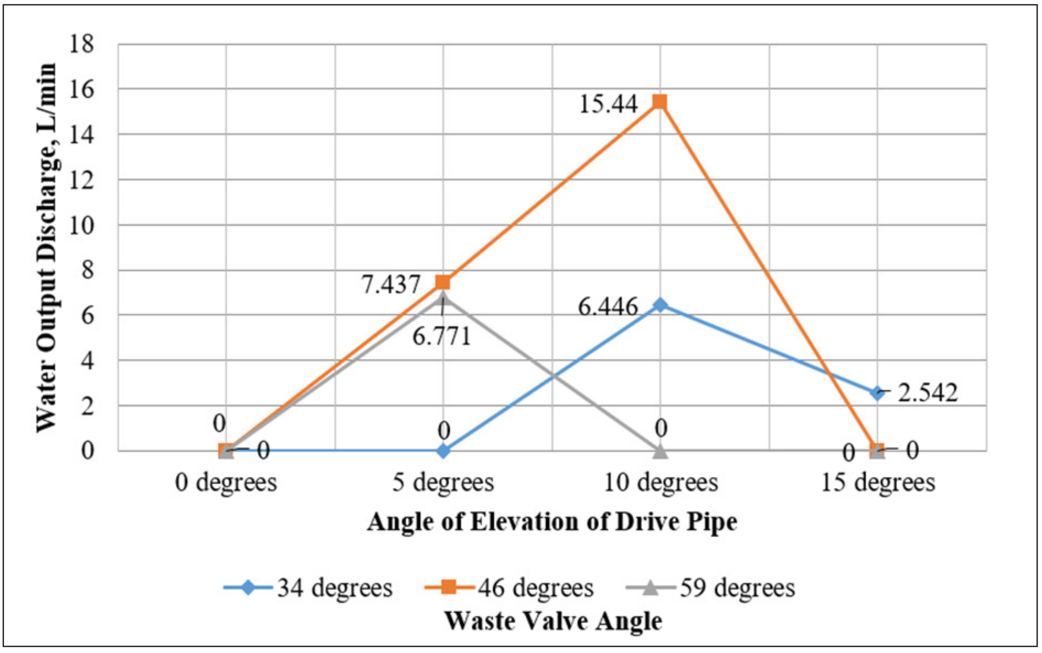

Figure 3. Water output discharge (L/min) of HRP as affected by drive pipe angle and waste valve angle using an output pipe of 1″ diameter

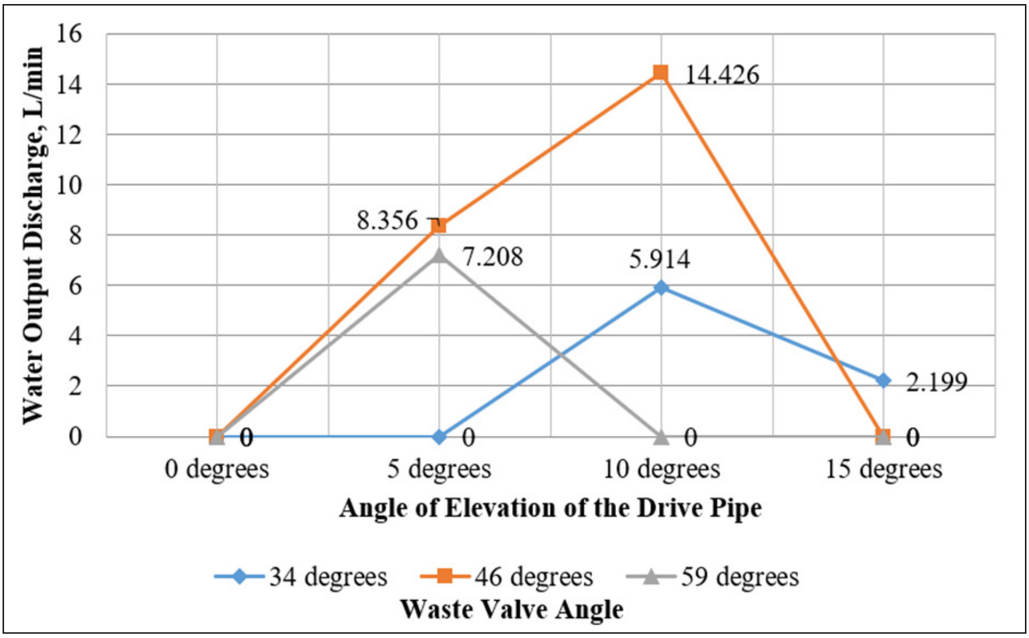

Figure 4. Water output discharge (L/min) of HRP as affected by drive pipe angle and waste valve angle using output pipe of 3/4″ diameter

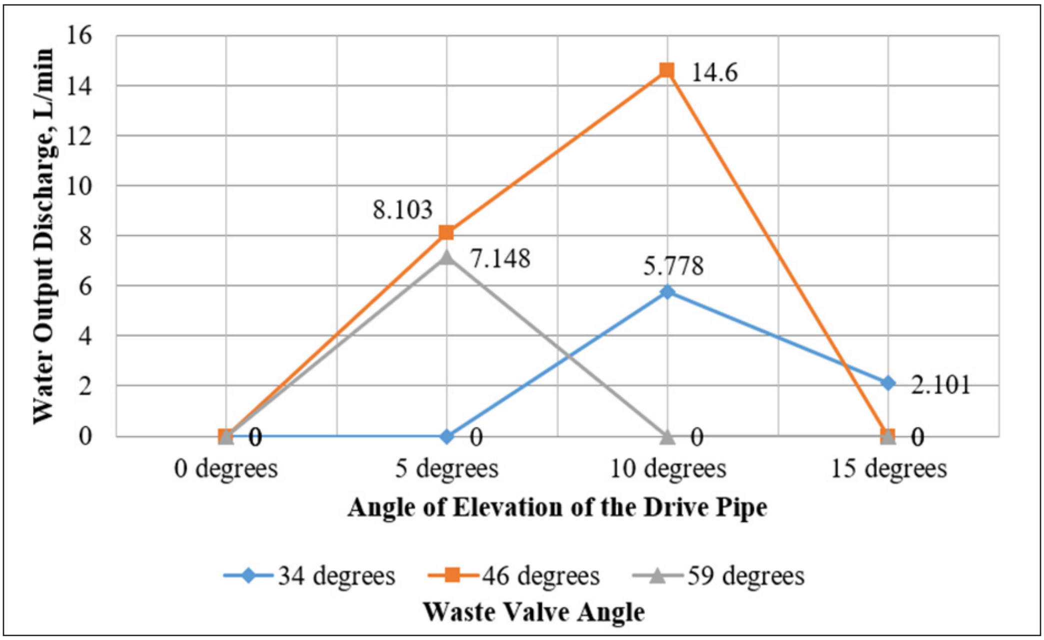

Figure 5. Water output discharge (L/min) of HRP as affected by drive pipe angle and waste valve angle using output pipe of 1/2″ diameter

Height of the Water Discharge

The data on the height of the water discharge of the HRP as affected by the different factors are presented in Table 5. The highest height was 6.38 m for T_{13} (H = 10°, Θ_w = 46°, Ø = 1/2″) and the lowest was 6.31 m for T_{11} (H = 10°, Θ_w = 34°, Ø = 3/4″) and T_{12} (H = 10°, Θ_w = 34°, Ø = 3/4″). Table 6 compares the ANOVA on the water discharge height affected by the three factors.

Table 5
Height (m) of water discharge at each treatment combination in three replications

Treatment (H, Θ_w, Ø)	**Replication**			**Mean**
	1	**2**	**3**	
T_1 (5°, 34°, 1/2″)	0	0	0	0
T_2 (5°, 34°, 3/4″)	0	0	0	0
T_3 (5°, 34°, 1″)	0	0	0	0
T_4 (5°, 46°, 1/2″)	7.84	8.43	8.04	8.10
T_5 (5°, 46°,3/4″)	8.24	8.02	8.81	8.36
T_6 (5°,46°,1″)	7.16	8.08	7.07	7.44
T_7 (5°, 59°, 1/2″)	7.58	7.00	6.87	7.15
T_8 (5°, 59°, 3/4″)	7.40	7.05	7.18	7.21
T_9 (5°, 59°, 1″)	6.72	6.90	6.70	6.77
T_{10} (10°, 34°, 1/2″)	6.04	5.56	5.74	5.78
T_{11} (10°, 34°, 3/4″)	5.72	6.00	6.02	5.91
T_{12} (10°, 34°, 1″)	6.40	6.38	6.56	6.45
T_{13} (10°, 46°, 1/2″)	14.62	14.31	14.87	14.60
T_{14} (10°, 46°, 3/4″)	14.64	13.80	14.84	14.43
T_{15} (10°, 46°, 1″)	15.29	15.63	15.40	15.44
T_{16} (10°, 59°, 1/2″)	0	0	0	0
T_{17} (10°, 59°, 3/4″)	0	0	0	0
T_{18} (10°, 59°, 1″)	0	0	0	0
T_{19} (15°, 34°, 1/2″)	2.15	1.86	2.29	2.10
T_{20} (15°, 34°, 3/4″)	2.22	2.24	2.13	2.20
T_{21} (15°, 34°, 1″)	2.39	2.96	2.28	2.54
T_{22} (15°, 46°, 1/2″)	0	0	0	0
T_{23} (15°, 46°, 3/4″)	0	0	0	0
T_{24} (15°, 46°, 1″)	0	0	0	0
T_{25} (15°, 59°, 1/2″)	0	0	0	0
T_{26} (15°, 59°, 3/4″)	0	0	0	0
T_{27} (15°, 59°, 1″)	0	0	0	0

Note : A 0 value means the HRP is not operating
H : Drive pipe angle or angle of elevation of the drive pipe
Θ_w : Waste valve angle or angle of inclination of the waste valve
Ø : Delivery or output pipe diameter size

Table 6
Analysis of variance (ANOVA) on the height (m) of the water discharge of the hydraulic ram pump as affected by drive pipe angle, waste valve angle, and output pipe size for three replications

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Statistic Value	p-value
Drive Pipe Angle (A)	2	80.62	40.31	4081254.88***	0.00
Waste Valve Angle (B)	2	79.57	39.78	4027974.13***	0.00
Output Pipe Size (C)	2	0.001	0.000	39.13***	0.00
A x B	4	643.46	160.87	16287631.63***	0.00
A x C	4	0.001	0.000	34.48***	0.00
B x C	4	0.003	0.001	65.75***	0.00
A x B x C	8	0.002	0.000	24.50***	0.00
Error	54	0.001	9.87E-6		
Total	80	803.65			

*** - very highly significant

The ANOVA indicates that the interaction among the drive pipe angle, waste valve angle, and output pipe size has a highly significant effect on the height of water discharge. However, the interaction effect between drive pipe angle and waste valve angle has the highest contribution to the differences in water discharge height. It accounts for 80.07% of the variation in water discharge height. Results of the comparison of the treatments with nonzero height of water discharge are presented in Table 7.

Table 7
Comparison of the mean height (m) of water discharge at different combinations of drive pipe angle (A), waste valve angle (B), and output pipe size (C)

Treatment (A,B,C)	Mean	Treatment (A,B,C)	Mean	Treatment (A,B,C)	Mean
T_{13} (10°, 46°, 1/2″)	6.3867^{a}	T_{4} (5°, 46°, 1/2″)	6.3433^{bc}	T_{5} (5°, 46°, 3/4″)	6.3300^{de}
T_{9} (5°, 59°, 1″)	6.3800^{a}	T_{15} (10°, 46°, 1″)	6.3400^{bcd}	T_{10} (10°, 34°, 1/2″)	6.3200^{ef}
T_{8} (5°, 59°, 3/4″)	6.3500^{b}	T_{20} (15°, 34°, 3/4″)	6.3333^{cd}	T_{6} (5°, 46°, 1″)	6.3200^{ef}
T_{7} (5°, 59°, 1/2″)	6.3500^{b}	T_{19} (15°, 34°, 1/2″)	6.3333^{cd}	T_{12} (10°, 34°, 1″)	6.3100^{f}
T_{14} (10°, 46°, 3/4″)	6.3467^{b}	T_{21} (15°, 34°, 1″)	6.3300^{de}	T_{11} (10°, 34°, 3/4″)	6.3100^{f}

*Means with the same letters are not significantly different at the 5% level of significance.

The results of Tukey's test (Table 7) show that treatment combinations T_{13} and T_9 produced the two highest heights, 6.3867 m and 6.38 m, respectively. The second three highest heights were 6.35 m, 6.35 m and 6.3467 m for T_8, T_7, and T_{14}, respectively. The shortest heights were 6.32 m, 6.32 m, 6.31 m, and 6.31 m, produced by T_{10}, T_6, T_{12}, and T_{11}, respectively.

The Pressure Developed Inside the Air Chamber

Table 8 presents the pressures developed inside the HRP's air chamber as affected by the different factors. The highest pressure of 68.95 kPa was recorded for T_6, T_7, T_8, T_9, T_{13}, and T_{14}, while the lowest pressure of 51.71 kPa was produced for T_{19}.

Table 8
Pressure (kPa) in the air chamber of the hydraulic ram pump at each treatment combination in three replications

Treatment (H, Θ$_w$, Ø)	**Replication**			**Mean**
	1	**2**	**3**	
T_1 (5°, 34°, 1/2″)	0	0	0	0
T_2 (5°, 34°, 3/4″)	0	0	0	0
T_3 (5°, 34°, 1″)	0	0	0	0
T_4 (5°, 46°, 1/2″)	65.50	65.50	65.50	65.50
T_5 (5°, 46°,3/4″)	62.05	62.05	62.05	62.05
T_6 (5°,46°,1″)	68.95	68.95	68.95	68.95
T_7 (5°, 59°, 1/2″)	68.95	68.95	68.95	68.95
T_8 (5°, 59°, 3/4″)	68.95	68.95	68.95	68.95
T_9 (5°, 59°, 1″)	68.95	68.95	68.95	68.95
T_{10} (10°, 34°, 1/2″)	60.33	60.33	60.33	60.33
T_{11} (10°, 34°, 3/4″)	60.33	60.33	60.33	60.33
T_{12} (10°, 34°, 1″)	55.16	55.16	55.16	55.16
T_{13} (10°, 46°, 1/2″)	68.95	68.95	68.95	68.95
T_{14} (10°, 46°, 3/4″)	68.95	68.95	68.95	68.95
T_{15} (10°, 46°, 1″)	62.05	62.05	62.05	62.05
T_{16} (10°, 59°, 1/2″)	0	0	0	0
T_{17} (10°, 59°, 3/4″)	0	0	0	0
T_{18} (10°, 59°, 1″)	0	0	0	0
T_{19} (15°, 34°, 1/2″)	51.71	51.71	51.71	51.71
T_{20} (15°, 34°, 3/4″)	60.33	60.33	60.33	60.33
T_{21} (15°, 34°, 1″)	60.33	60.33	60.33	60.33
T_{22} (15°, 46°, 1/2″)	0	0	0	0
T_{23} (15°, 46°, 3/4″)	0	0	0	0
T_{24} (15°, 46°, 1″)	0	0	0	0

Table 8 (*continue*)

Treatment (H, Θ_w, Ø)	Replication			Mean
	1	2	3	
T_{25} (15°, 59°, 1/2″)	0	0	0	0
T_{26} (15°, 59°, 3/4″)	0	0	0	0
T_{27} (15°, 59°, 1″)	0	0	0	0

Note: A 0 value means the HRP is not operating
H: Drive pipe angle or angle of elevation of the drive pipe
Θ_w: Waste valve angle or angle of inclination of the waste valve
Ø: Delivery or output pipe diameter size

Table 9 gives the ANOVA for the pressure build-up in the air chamber. It indicates that the interaction between drive pipe angle, waste valve angle, and output pipe size has a highly significant effect on pressure. However, the interaction effect between the drive pipe angle and waste valve angle is the most important, as it can explain 78.66% of the variation in the pressure readings.

Table 9
Analysis of variance (ANOVA) for the pressure in the air chamber (kPa) of the hydraulic ram pump as affected by drive pipe angle, waste valve angle, and output pipe size for three replications

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F Statistic Value	p-value
Drive Pipe Angle (A)	2	10609.33	5304.665	2.441E + 29***	0.00
Waste Valve Angle (B)	2	6472.69	3236.34	1.49 E + 29***	0.00
Output Pipe Size (C)	2	5.94	2.97	1.37E + 26***	0.00
A x B	4	64328.67	16082.17	7.40E + 29***	0.00
A x C	4	164.52	41.13	1.89E + 27***	0.00
B x C	4	39.64	9.91	4.56E + 26***	0.00
A x B x C	8	158.60	19.83	9.12E + 26***	0.00
Error	54	1.17E-24	2.17E-26		
Total	80	81779.39			

*** - very highly significant

Hrp Volumetric Efficiency

Table 10 presents the HRP's volumetric efficiencies as affected by the different factors. The combination of 10° drive pipe angle and 34° waste valve angle using 1″ diameter output pipe produced the highest HRP volumetric efficiency of 92.46%, while the combination of 15° drive pipe angle and 34° waste valve angle using 1″ diameter output pipe gave the lowest HRP volumetric efficiency of 45.63%.

Table 10
Volumetric efficiency of the Hydraulic Ram Pump (HRP) at each treatment combination in three replications

Treatment ($H, \Theta_w, Ø$)	**Replication**			**Mean**
	1	**2**	**3**	
T_1 (5°, 34°, 1/2″)	0	0	0	0
T_2 (5°, 34°, 3/4″)	0	0	0	0
T_3 (5°, 34°, 1″)	0	0	0	0
T_4 (5°, 46°, 1/2″)	92.23	90.48	89.06	92.23
T_5 (5°, 46°,3/4″)	84.91	92.73	89.28	84.91
T_6 (5°,46°,1″)	87.78	79.55	82.38	87.78
T_7 (5°, 59°, 1/2″)	57.37	56.93	58.73	57.37
T_8 (5°, 59°, 3/4″)	59.36	60.39	60.27	59.36
T_9 (5°, 59°, 1″)	57.08	54.72	55.94	57.08
T_{10} (10°, 34°, 1/2″)	64.86	69.88	69.21	64.86
T_{11} (10°, 34°, 3/4″)	72.07	68.33	69.93	72.07
T_{12} (10°, 34°, 1″)	92.58	95.56	92.46	92.58
T_{13} (10°, 46°, 1/2″)	60.14	63.75	61.77	60.14
T_{14} (10°, 46°, 3/4″)	53.21	56.44	55.16	53.21
T_{15} (10°, 46°, 1″)	56.08	54.49	55.17	56.08
T_{16} (10°, 59°, 1/2″)	0	0	0	0
T_{17} (10°, 59°, 3/4″)	0	0	0	0
T_{18} (10°, 59°, 1″)	0	0	0	0
T_{19} (15°, 34°, 1/2″)	43.40	50.52	46.84	43.40
T_{20} (15°, 34°, 3/4″)	59.46	52.91	55.43	59.46
T_{21} (15°, 34°, 1″)	49.71	41.87	45.63	49.71
T_{22} (15°, 46°, 1/2″)	0	0	0	0
T_{23} (15°, 46°, 3/4″)	0	0	0	0
T_{24} (15°, 46°, 1″)	0	0	0	0
T_{25} (15°, 59°, 1/2″)	0	0	0	0
T_{26} (15°, 59°, 3/4″)	0	0	0	0
T_{27} (15°, 59°, 1″)	0	0	0	0

Note: A 0 value means the HRP is not operating
H: Drive pipe angle or angle of elevation of the drive pipe
Θ_w: Waste valve angle or angle of inclination of the waste valve
Ø: Delivery or output pipe diameter size

CONCLUSION AND RECOMMENDATIONS

A suitable rig for testing hydraulic ram pumps is essential for confirming the pump's optimal performance. The combination of 10° drive pipe angle, 46° waste valve angle and 1.0″ diameter output pipe provided the highest mean output discharge of 15.440 L/min.

The combination of 10° drive pipe angle, 34° waste valve angle, and 1.0″ diameter output pipe resulted in the highest mean HRP volumetric efficiency of 92.46%. The combination of 10° drive pipe angle, 46° waste valve angle, and 0.5″ diameter output pipe provided the highest mean pressure of 68.95 kPa and the highest mean water delivery head of 6.38 m. The study suggests the provision of a bigger water supply tank and a continuous water source for the operation of the HRP. A waste water tank below the HRP support assembly is recommended to collect the wastewater and pump it again to the water supply tank. Longer drive pipes are recommended when using the testing rig to achieve higher delivery head and output discharge. Also, pipe fittings and elbows need to be eliminated from the design because they cause energy loss, resulting in a decrease in the delivery head and output discharge. Further study using different HRP designs is recommended to come up with an optimum HRP design for promotion in rural areas.

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