INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

ORIGINAL ARTICLE

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OPEN ACCESS

Received: 01/03/2025

Accepted: 18/04/2025

Published: 14/05/2025

Citation: Rahman M (2025) Optimizing Hydraulic Ram Pump Performance: Experimental Insights on Waste Valve Height and Uncertainty Analysis. Indian Journal of Science and Technology 18(18): 1377-1396. https://doi.org/10.17485/IJST/v18i18.394

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Optimizing Hydraulic Ram Pump Performance: Experimental Insights on Waste Valve Height and Uncertainty Analysis

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Abstract

Objectives: This study examines how influencing characteristics, particularly waste valve height, affect hydraulic ram pump (HRP) performance. The goal is to find the best parameter configuration for the HRP to optimise the efficiency. It operates based on the principle of the water hammer effect. This effect generates its operational energy by pumping water from a lower elevation to a higher elevation. A system has been built to study how changing the height of the waste valve affects the flow rate of the ram pump, using different parts and assemblies. **Method:** The L/D ratio should range from 150 to 1000 for optimal operation of the ram pump. In this study, laminar flow has been assumed for the entirety of the investigation. Each cycle is often divided into three phases: acceleration, delivery and recoil. The water hammer effect, originating in the water itself, results in a loss of input water due to spillage. The delivery pipe dispenses a minimal quantity of water at the outlet. This research examines the effectiveness of an HRP by altering its most significant parameter—the height of the waste valve. **Findings:** The efficiencies recorded for five distinct experimental sets, corresponding to Waste Valve Heights (WVH) of 17 cm, 14 cm, 13 cm, 12 cm, and 11 cm, are 59.21%, 59.56%, 60.79%, 68.61%, and 55%, respectively. **Novelty:** This study determined that the parametric influence of waste valve height on the performance and efficiency enhancement of the Hydraulic Ram Pump is a significant factor. The study illustrates that Waste Valve Heights (WVH) considerably affect HRP performance and also boost performance in the newly built model.

Keywords: Hydram; Pressure Chamber; Waste valve; Water Hammer; Influencing Parameter; D'Aubuisson's Efficiency

1 Introduction

Many experimental studies examining the impact of hydraulic ram pump parameters on optimal performance have been conducted by numerous researchers across various nations, involving the manufacturing of hydraulic ram pumps (also known as Hydrams) and the execution of feasibility analyses. Researchers have demonstrated that the components, specifically the Pressure Chamber Height (PCH) and Waste Valve Height (WVH), have a crucial impact in the operation of the Hydraulic Ram Pump. The operation of the HRP is predicated on the principle of the water hammer effect. However, a ram pump operates solely on the energy derived by water hammer, making it a primary factor among others. A sudden closure of a valve in any pipe system is seen. The water hammer effect occurs when a rapidly moving liquid is abruptly halted, resulting in a high-pressure surge. Consequently, it results from an increase in pressure that generates a high-pressure shock wave propagating through pipes when the flow is compelled to alter its direction or cease abruptly. It will occur when an open flow is abruptly halted or when a pump ceases operation, occasionally resulting in flow reversing direction and producing backflow. Although it appears innocuous, the effect on the pipeline is a significant worry, and in certain cases, it may surpass ten times the system's working pressure. Despite its disadvantages, it can be employed beneficially in numerous technical procedures. This idea fully exploits the adverse effects of the water hammer phenomenon to generate pressure, allowing a segment of the input water that drives the pump to be raised above its source. The system operates only on water pressure, resulting in significant water loss, since over 75% of the supplied water is squandered[(1)] at the waste valve, hence diminishing pump efficiency. Therefore, optimizing the settings is crucial for achieving improved performance of the hydram.

Current studies on hydraulic ram pumps (HRPs) are deficient in thorough experimental and modeling methodologies with validation. The majority of studies concentrate on particular design elements (e.g., pipe characteristics, valve arrangements, chamber measurements) instead of adopting a comprehensive strategy that assesses the cumulative effect of all variables. Further, Experimental investigations on diverse dimension combinations are limited. Systematic alterations of parameters including inlet/outlet pipe diameters, valve dimensions and configuration, and pressure chamber characteristics (PCH, PCV) are essential for improving comprehension and optimization. HRP optimization necessitates the identification of essential design elements and their best configurations to enhance efficiency, dependability, and sustainability. Practical applications necessitate comprehensive investigation into dimensional variations and operational parameters (e.g., driving head, inlet head). Research should investigate the positioning of the outlet delivery pipe to enhance pressure surge efficiency, as proposed by Sarma et al.[(2)]

Future research ought to utilize AI and simulation techniques such as COMSOL Multiphysics for accurate optimization, enhancing HRP efficiency and longevity across various applications.

Numerous studies on Hydraulic Ram Pump (HRP) performance evaluation, as conducted by [3-5], have employed various methodologies including ANSYS, the Taguchi method, Genetic Algorithms, Multivariate Simulation, and Comsol Multi-Physics[(3)]. However, research aimed at predicting the impact of Waste Valve Height on performance optimization through empirical investigation is notably limited.

2 Methodology of Experimentation - Materials and Methods

The research on supply head, air chamber pressure, and waste valve beats per minute was individually adjusted throughout the hydram testing[(4)]. A study was performed to assess the impact of waste valve tuning on hydraulic performance by modifying the weight and stroke of the waste valve[(5)].

A systematic experiment was undertaken to ascertain the D'Aubuisson efficiency of a hydraulic ram pump by adjusting the height of the waste valve to locate the optimal setting for maximum efficiency. The experimental configuration included a constant-head water supply, a hydraulic ram pump equipped with a driving pipe, delivery pipe, air chamber, and an adjustable waste valve. The pump was operated at various waste valve heights, which are depicted in TR-1 to TR-5 in Figure 3(a) to 3(e), are in consistent increments. For each setting, the volume of water delivered through the delivery pipe and the volume wasted through the waste valve were measured during a predetermined duration, generally 10 minutes. The supply and delivery heads were consistent during all experiments to guarantee precision and uniformity. The efficiency was subsequently determined with the D'Aubuisson formula:

$$\frac{Q_D H_D}{Q_S H_S} = \frac{w \times h}{(w+W) \times h} \tag{1}$$

where *Qd* is the volume of water delivered, *Qs* is the total supply of water (delivered plus squandered), *Hd* is the delivery head, and *Hs* is the supply head. All experiments were conducted repeatedly to derive average values and minimise experimental error. The data was analysed and graphed to ascertain the correlation between waste valve height and efficiency, ultimately discovering the height that yielded the maximum D'Aubuisson efficiency. The performance is crucial in determining the relative position of the input-pressure chamber (compressor)-waste (ICW), and fluctuations in the height of the pressure chamber[(6)] influence the efficiency of Hydrams. A setup has been built to investigate the influence of the primary parameter—the height of the waste valve—on the output flow rate of the ram pump, consisting of various assemblies and components. The pump model was assembled utilizing the components enumerated in Table 1 and illustrated in Figure 4. The ratio of supply pipe length (Ls) to supply pipe diameter (L/D) is set at 152, with the drive pipe length (L) being 2.5 times the head[7]. The L/D ratio must be between 150 and 1000 for optimal ram pump functioning[8]. The erratic turbulence has been disregarded[9], and laminar flow has been presumed throughout the entire study.

2.1 Methodology of Experimentation - Components for Test Rig:

Table 1. Components of Test-Rig

S.I. no.	Component	Material	Dimension
1	Supply Pipe	UPVC	$\frac{3}{4}$ inch Diameter
2	Delivery Pipe	UPVC	1inch Diameter
3	Waste Valve	G.I.	1inch Diameter
4	Delivery Valve	G.I.	1inch Diameter
5	Check Valve	PVC	1 inch Diameter
6	Supply Tank	Plastic	Volume 200L, Diameter 0.75m
7	PVC Chamber	Plastic	3L
8	Tee	PVC	1 inch Diameter
9	Elbow	PVC	1 inch Diameter
10	Nipple	G.I.	1 inch Diameter
11	Reducer	PVC	0.5 inch Diameter
12	Overhead Tank to supply Tank	PVC	1000 L
13	Pressure Transmitter x 2	Instrument	Inlet & Outlet :(4-20) mA,0-10bar
14	Data Acquisition	Instrument	Keysight IO, Agilent Bench Link Data Logger,

The proposed model has been connected utilizing the following components for the Test Rig fabrication as shown in Table 1, and connected in the following orders:

1. One end of the PVC supply pipe is fitted with the supply tank with the help of a tank nipple and the other end is connected with the body of the Ram pump.
2. A check valve is connected between them which regulates the flow of fluid into the pump.
3. The waste valve and delivery valve are fitted as shown in figure.
4. The waste valve is fitted in such a way that its flap is initially open due to its self- weight. The delivery valve is placed so as to prevent backflow of water due to forces in the pressure chamber.
5. A pressure chamber is fitted above the delivery valve with a nipple and a reducer
6. A delivery pipe which connects the pump system to the delivery tank is placed between the pressure chamber and delivery valve with the help of T joint.

2.1.1. Operation:

The operational steps involved[10] in the working of a hydraulic ram pump are shown in Figure 1 below:

Section-A: constant hydraulic head is considered at the upstream end of the drive pipe.

Section-B: branching junction condition is applied at the downstream end of the drive pipe.

Section-C: branching junction condition is applied at the upstream end of the waste pipe.

Section-D: the discharge is regulated at the downstream end of the waste pipe by means of an inverted check valve releasing to atmosphere.

Section-E: branching junction condition is applied at the upstream end of the delivery pipe.

Section-F: the discharge is regulated at the downstream end of the delivery pipe by means of a check valve connected to the air chamber.

Step 1: Water enters the body of the ram pump through the inlet pipe and exits through the waste valve which is in opened position when the system is in starting position.

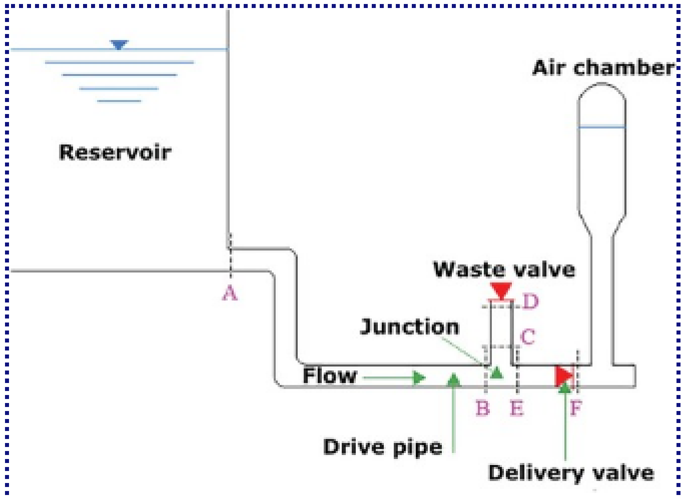

Fig 1. Schematic of the hydraulic ram pump system

Step 2: As the water enters the ram pump, it gains increased velocity and momentum, thereby forcing the waste valve to close. When the waste valve abruptly closes, the flow ceases instantaneously, resulting in a water hammer effect that produces a pressure spike. The elevated pressure propels the water via the delivery valve into the pressure chamber, where the air volume expands to equilibrate the pressure, subsequently driving the water through the delivery pipe. The generated pressure also propels a portion of the water into the inlet pipe, ensuring a constant flow.

Step 3: Once the water has returned via the intake pipe, a standard pressure wave travels from the inlet pipe to the check valve, while the delivery valve remains slightly ajar, allowing water to enter the air chamber.

Step 4: When the normal pressure wave reaches the waste valve, a reduced pressure is generated in the inlet pipe, causing the valves to experience significantly lower pressure than previously, allowing the waste valve to reopen and the delivery valve to close.

Step 5: Subsequently, a normal pressure wave propagates through the inlet pipe, and the cycle is reiterated. Consequently, the pump operates intermittently; nevertheless, the pressure chamber converts the intermittent flow into a relatively steady one.

2.1.2. Data Logging:

The DAQ has been utilised to monitor data through an electrical current generated by a Current Transducer (CT), as illustrated in Figure 2(b). The software utilised for this experiment includes Keysight IO, Agilent Bench Link Data Logger, and BenchVue. The Keysight 34972A Data Acquisition Unit comprises a three-slot mainframe featuring an integrated 6 1/2 digit digital multimeter. Two ASPT series pressure transducers were employed to measure the input and output pressure of the Ram pump utilising the data acquisition system (DAQ) shown in Figure 2(a). The selected current range for inlet and outlet transducers was 4-20 mA, while the pressure range was 0-10 Bar.

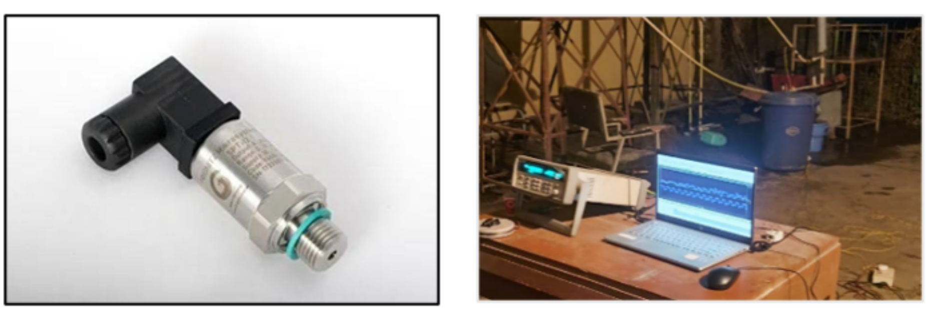

Fig 2. (a). Pressure transducer- 4-20mA. (b). Data Acquisition (DAQ) of Test Rig

2.1.3. Working Principle:

Let L represent the Drive Pipe Length, W denote the weight of water flowing into the chamber per second, w signifies the weight of water elevated per second, h indicates the height of water in the supply tank above the chamber, and H represents the height of water raised from the chamber.

The energy supplied by the supply tank to the ram pump is calculated as the product of the weight of water supplied and the height from which it is supplied, expressed as

$$W \times h \tag{2}$$

The energy delivered by the ram pump is defined as the product of the weight of water raised and the height through which it is elevated, represented as

$$w \times H \tag{3}$$

The energy provided by the supply tank to the ram pump therefore equals the weight of water supplied times the height from which it is supplied, which is W; the energy produced by the ram pump equals the weight of water raised times the height through which it is raised, which is expressed as

$$w \times H$$

Therefore, efficiency is calculated as the ratio of energy delivered by the ram to energy supplied by the ram.

So, the Efficiency is-

$$\frac{Q_D H_D}{Q_S H_S} = \frac{w \times h}{(w+W) \times h} \tag{4}$$

The efficiency η_A is known as D'Aubuisson's efficiency [11].

Supply pipe diameter = 1inch, Supply pipe length = 2.9 m, Delivery pipe diameter = 1inch

Firstly, the pump is run for 10 minutes then the displacement of liquid level in the supply tank is measured (Displacement of water level) (L) = 2 inch = 0.0508m, (Diameter of supply tank (d_1) = 75cm = 0.75m, Hence, the volume of the liquid supplied from the tank is calculated as-

$$Vs = \frac{\pi}{4} \times d_1^2 \times L = \frac{3.14}{4} \times 0.75^2 \times 0.0508 = 0.022428 \text{ m}^3 \tag{5}$$

Where, d_1 = Inner diameter of the supply tank, l = Level of water displaced in time$t$ = 600s, Supply flow rate, $Qs = 0.022428/600 = 3.738 \times 10 - 5\text{m}^3/\text{sec}$ and using the Continuity **eqn. 5** the flow velocity, Vs will be $Qs/As = 0.074\text{m/s}$

$$[\text{As for 1-inch inlet pipe} = 0.0005064506 \text{ m}^2] \tag{6}$$

2.1.4. Test Rigs for Experimentation:

The experimental investigation was done by altering the WVH from 17 to 11 cm and for each configuration a test-run is done using DAQ system whose graphical representation are plotted in the subsequent section respectively with following specifications - Inlet Pipe Diameter Di: 25.4 mm, Outlet Pipe Diameter D_O = 25.4 mm, Water Tank Volume, Vs = 200 L, Height of Water Supply, h = 1700 mm.

Height of Water Discharge H = 2950mm, Waste valve Discharge, W = 1.53 L/min, Outlet Discharge, w = 0.4 L/min; Using D'Aubuisson's relation from **equation (3)** efficiencies are found.

Each test rig is configured with specific parameters including wastage valve height (WVH), pressure chamber height (PCH) [2], and horizontal distance between the air chamber and wastage valve (HD). These parameters are crucial in determining the performance and efficiency of the HRP. The test rigs developed for experimental studies on ram pumps are presented below for illustration. The configurations, components, and setup of the test rigs were described in detail, including

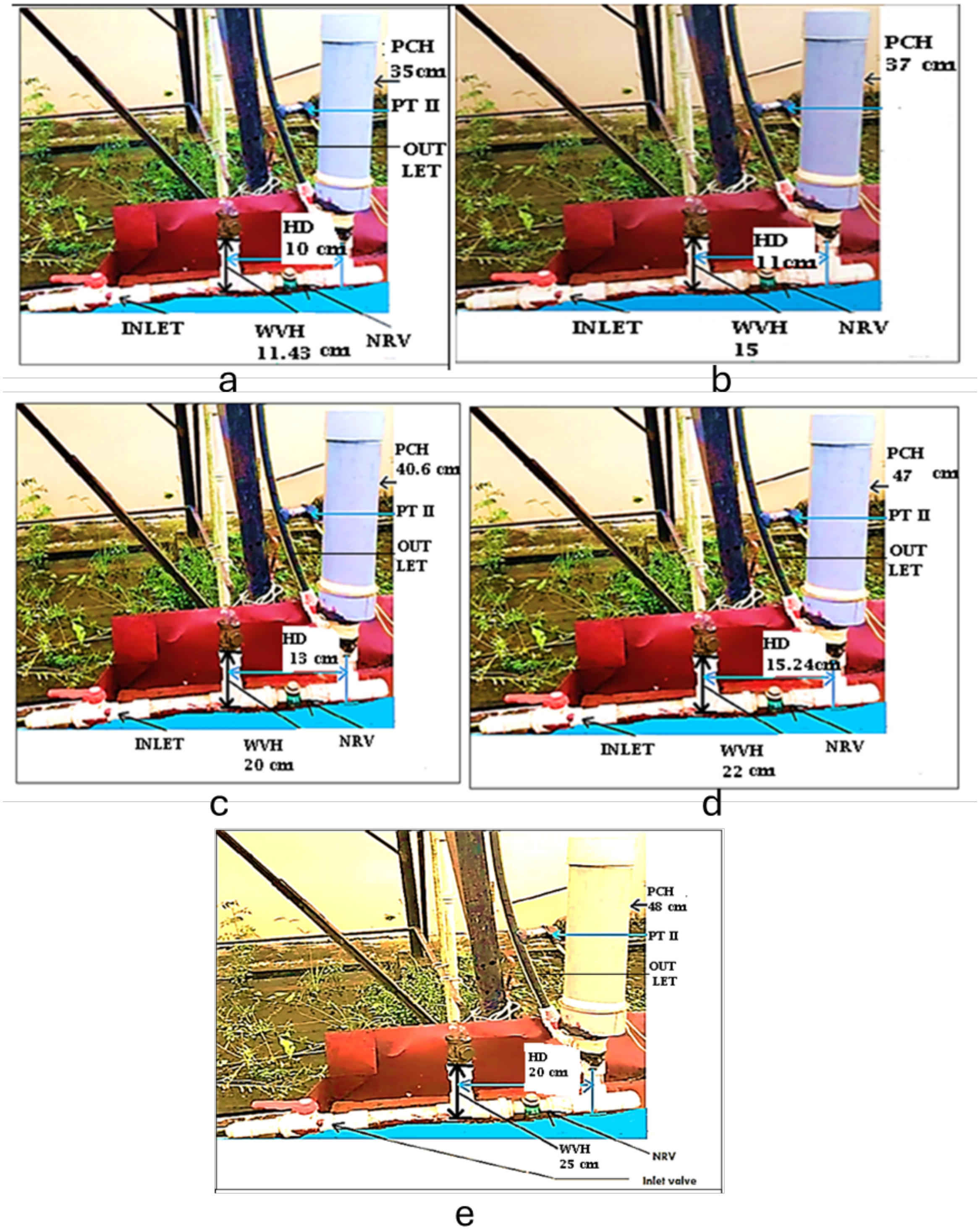

Fig 3. (a) Test Rig-1, (b) Test Rig -2, (c) Test Rig -3, (d) Test Rig -4, (e)Test Rig -5

Table 2. Discharge Through Delivery Pipe

SL. no.	Time (min)	Water lifted (L)	Water wasted (L)
1	10	4.2	15
2	10	4	16.5
3	10	3.8	14.5
Average L/min	10	0.4	1.53

Table 3. Parameter for Test Rig-1 and Test Rig-2

Parameter	TR-1(cm)	TR-2(cm)
Waste valve height	11.43	15.00
Pressure chamber height	35.00	37.00
Horizontal distance between WV and PC	10.00	11.00

Table 4. Parameter for Test Rig-3 and Test Rig-4

Parameter	TR-3 cm	TR-4 cm
Waste valve height	20.0	22.00
Pressure chamber height	40.6	47.00
Horizontal distance between WV and PC	13.0	15.24

the materials used. The following Figure 3(a) to 3(e) show the dimensions and specifications for all the TRs undergoing for the test runs. The selected parameters for each TR- 1 and TR- 2 are shown in Table 3.

The selected parameter for each TR 3 and TR 4 is shown in Table 4.

The selected parameter for each TR - 5 is shown in Table 5.

Table 5. Parameter for Test Rig-5

TR-5 (cm)	Unit (cm)
Waste valve height	25
Pressure chamber height	48
Distance between WV and PC	20

Extensive research has been done on the processes and techniques for doing tests on the built test rigs (TR) meant for HRP. The built Test Rigs show variance in Waste Valve Height (WVH), Pressure Chamber Height (PCH), and Horizontal Distance (HD), which is then analyzed. The study[3] underlined the interaction effect of WVH and PCH, which is the main subject of this section, combined with the horizontal distance between PC and WV (HD), which was previously ignored. Table 6 below shows the results obtained from the best combinations.

Table 6. Test Rigs Efficiency Vs Delivery Flow rate

TR	Efficiency %	Delivery Flow rate $10^{-2} \times \left(\frac{kg}{s}\right)$
TR-1	16.44	0.02949
TR-2	26.44	0.03740
TR-3	9.66	0.06121
TR-4	13.10	0.24896
TR-5	20.13	0.50990

The data reveal that the efficiency and flow rate of the various test rigs fluctuated based on their configurations. TR-5 displayed the highest flow rate, while TR-2 exhibited the greatest efficiency. Among all test rigs, TR-3 showed the lowest efficiency. The reduced performance noted in TR-1, TR-3, TR-4, and TR-5 is due to the interactions among parameter modifications, leading to diminished efficiency and flow rate. Furthermore, several factors, including variations in parametric design changes and operational conditions, contribute to these suboptimal efficiencies. To improve the effectiveness of the experimental test rigs and comprehend the underlying causes of these discrepancies, further investigation and evaluation are conducted with the

Optimised Test Rig (OTR) outlined in Table 7, which highlights the most advantageous combination. Any inconsistencies or unexpected observations are also examined for additional analysis.

Table 7. Parameters for Test Rigs (optimized)

Model	WVH (cm)	PCH (cm)	HD (cm)
TR-1	11.43	35.00	10.00
TR-2	15.00	37.00	11.00
TR-3	20.00	40.60	13.00
TR-4	22.00	47.00	15.24
TR-5	25.00	48.00	20.00

3 Results and Discussion

The experimental and theoretical investigations on hydrams to ascertain the relationship between pumping rate and wastage, concluding that the velocity in the drive pipe is the determining factor. This study conducted an analysis, focusing on the optimal OTR, with a sole parameter variation—Waste Valve Height—examined individually in each configuration. In a study, the Waste Valve Heights of 11.43 cm as essential factors for optimizing HRP performance [2] was investigated. Therefore, in the present experiment, WVH were deliberately selected from this range to improve outlet flow efficiency, as indicated in Table 8.

Table 8. Variation of WVH Vs Efficiency

WVH (cm)	Delivery Flow $\times\left(\frac{kg}{s}\right)$	Supply Flow $\times\left(\frac{kg}{s}\right)$	D'Aubuisson Efficiency (%)
17	0.02390	0.04335	59.21
14	0.03053	0.05993	59.56
13	0.03130	0.05956	60.79
12	0.03619	0.05690	68.61
11	0.03323	0.07340	55.00

The performance and efficiency of an HRP are greatly affected by the elevation of its waste valve. Differences in the waste valve height ranging from 11 to 17 cm significantly affect the operation of the HRP. The corresponding inlet and outlet pressures are illustrated in Figure 4(a) to 4(f) and Figure 5(a) to 5(d). An extremely low valve height may lead to significant water leakage before adequate pressure accumulates, resulting in a diminished pressure increase and, thus, reduced performance. Conversely, an increase in height enhances efficiency; however, additional elevation may provide diminished output.

Examinations on HRPs were conducted by independently altering the affecting elements, including inlet head, pressure chamber, and wastage valve pulses per minute [4]. Research was conducted to assess the effect of waste valve modification on Hydram performance by modifying the stroke and weight of the waste valve. The speed at which the wastage valve closes is the most crucial characteristic influencing hydraulic ram function. The design and configuration of the waste valve, the elevation of the supply head [12], and the length of the driving pipe are the determining criteria. Incorporating an elastic seal at the waste and delivery valves to provide a cushioning effect and diminish noise could significantly enhance efficiency.

The performance characteristics of the pump exhibit distinct variations upon raising the waste valve height from 11 cm to 17 cm. have been studied and represented graphically in Figure 4(a) to 4(f) and Figure 5(a) to 5(d) for both inlet and outlet in all cases as discussed under.

The inlet and outlet pressure curves for WVH of 17 cm are shown above in Figure 4(a) and 4(b) for a duration of 10 minutes run. The model has been validated by comparing the inlet and outlet pressure profiles.

Similarly, the model comprising of WVH of 14 cm is subjected to experimental study. The inlet and outlet pressure curves are shown below in Figure 4(c) and 4(d) for a duration of 10 minutes. The model has been validated by comparing the inlet and outlet pressure profiles.

The model comprising of parameters of WVH of 13 cm is subjected to experimental study. The inlet and outlet pressure curves are shown below in Figure 4(e) and 4(f) for a duration of 10 minutes.

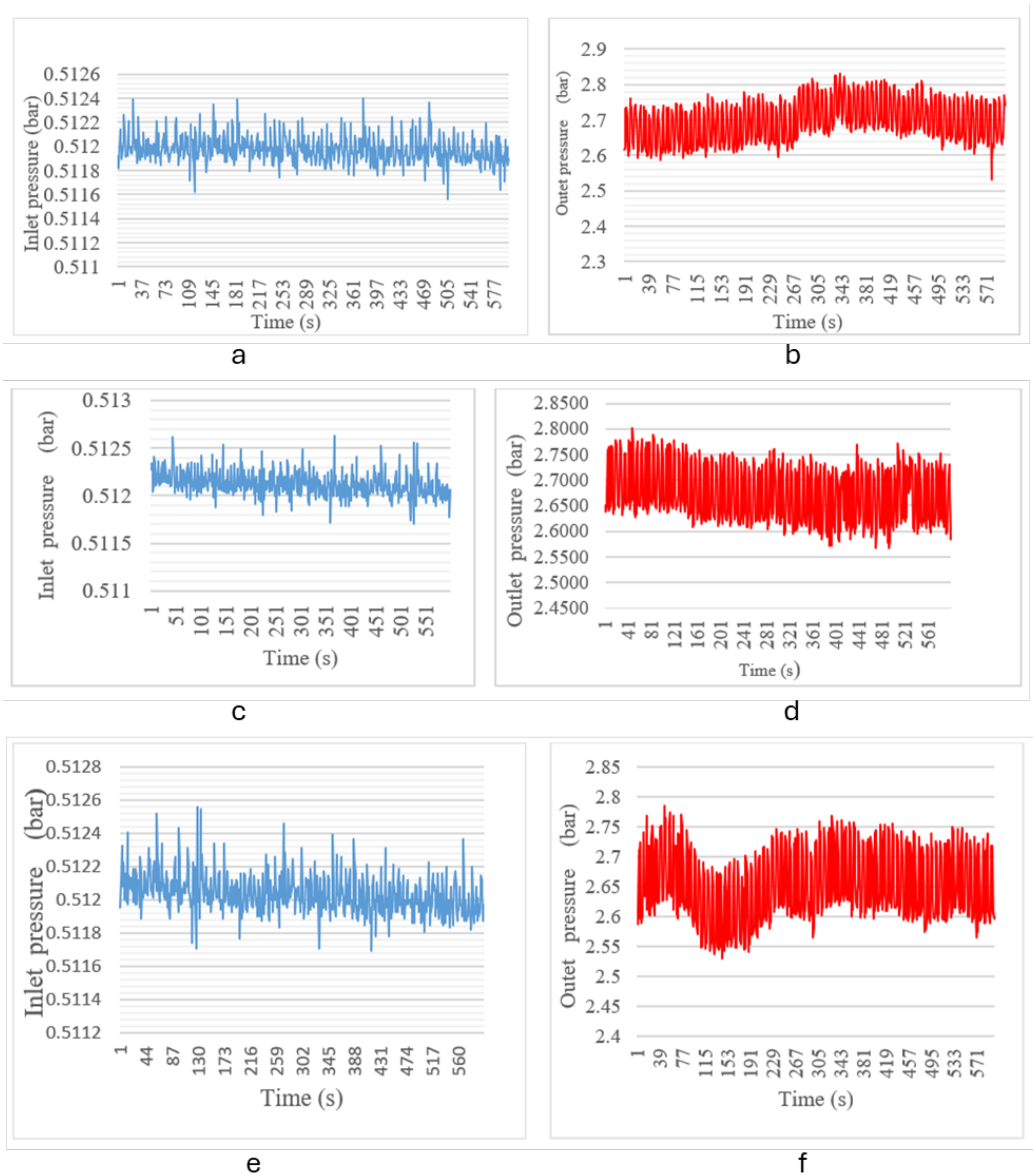

Fig 4. (a) Inlet pressure at WVH 17 cm, (b) Outlet pressure at WVH 17 cm, (c) Inlet pressure at WVH14 cm, (d) Outlet pressure at WVH 14 cm, (e) Inlet pressure at WVH 13 cm, (f) Outlet pressure at WVH 13 cm

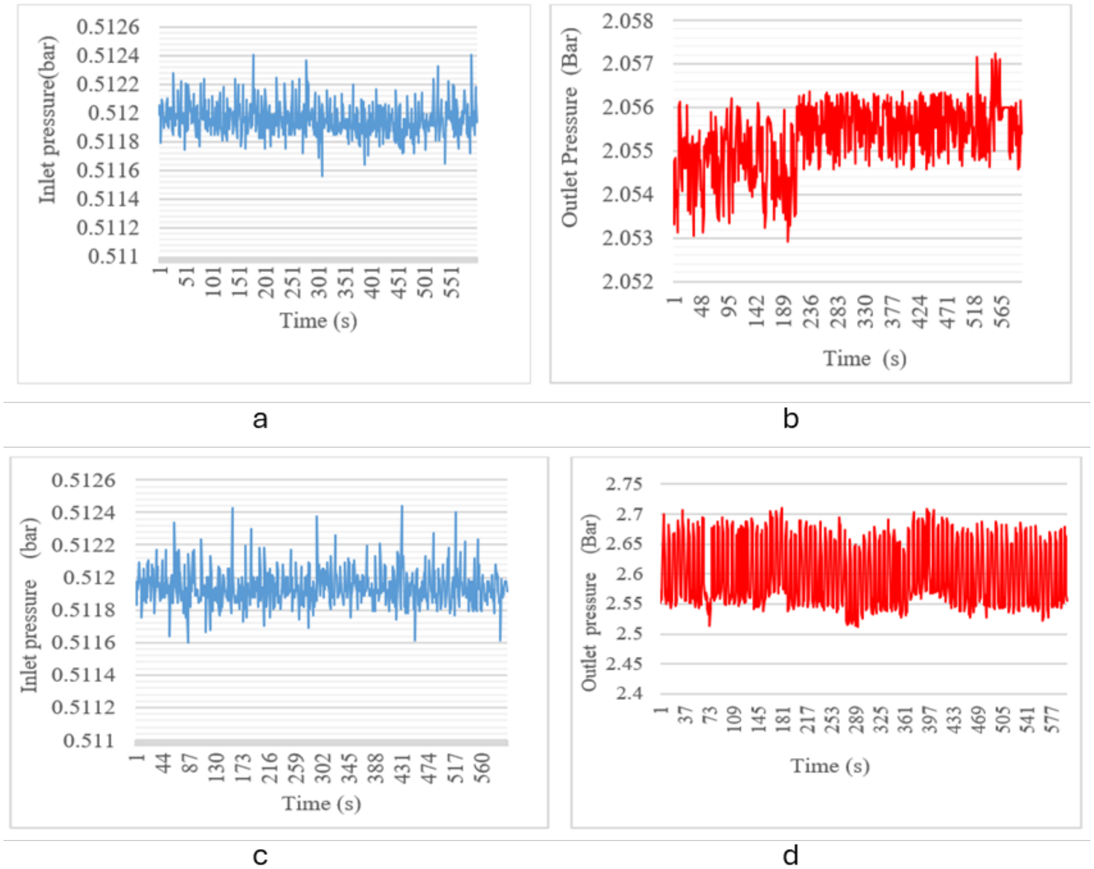

Fig 5. (a) Inlet pressure at WVH 12 cm, (b) Outlet pressure at WVH 12 cm, (c) Inlet pressure at WVH 11 cm, (d) Outlet pressure at WVH 11 cm

The model comprising of parameters of WVH of 12 cm is subjected to experimental study. The inlet and outlet pressure curves are shown below in Figure 5(a) and 5(b) as above for a duration of 10 minutes.

Lastly, the final model comprising of the parameter of WVH of 11 cm is subjected to experimental study. The inlet and outlet pressure curves are shown in Figure 5(c) and 5(d) for a duration of 10 minutes to validate by comparing the inlet and outlet pressure profiles. The relevant curve for the Delivery, Waste and Total flow are presented in Figure 6.

To measure the current of pressure sensors which are connected at inlet and outlet pipes where two nos. of Current Transducer (CT) have been mounted. Current, I is measured from DAQ while using pressure transducer in Figure 2(a) with ranges, I = 4-20 mA, P = 0-10 Bar and it is found I is 4.8219 mA and 7.28 mA for inlet and outlet flow. These Pressures were converted using linear interpolation as shown in **Eq. (7)**,

Putting I = 4.8219,

$$\frac{4.8219-4}{20-4}=\frac{P-0}{10-0}\gg P=0.513\text{ bar} \tag{7}$$

$$\text{Similarly, for outlet pressure, } I\ = 7.28\text{mA, giving, } P=2.05\text{ Bar} \tag{8}$$

At a waste valve height of 11 cm, diminished water is diverted to the delivery pipe when the waste valve functions at a reduced pressure. Conversely, when the waste valve level is elevated to around 12 cm, the opening pressure of the waste valve increases, facilitating optimal valve tuning and allowing a greater volume of water to be redirected to the supply pipe during each operational cycle. Reduced discharge rates may occur due to a limitation in water flow via the pump at diminished waste valve elevations. For all parameter values of 17, 14, 13, 12, and 11 cm concerning the change of WVH, pressure differentials

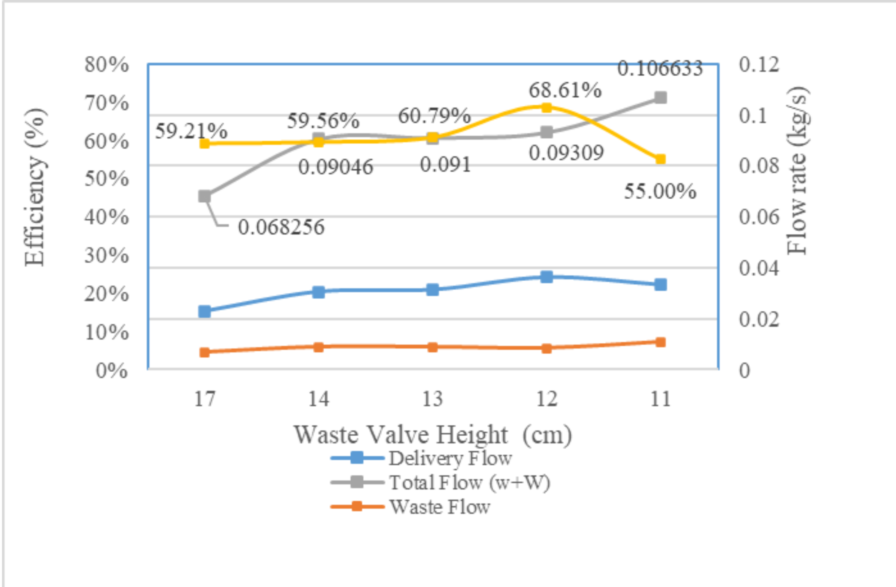

Fig 6. Variation of WVH Vs Efficiency

are present between the inlet and exit profiles. The pressure in the output pipe of an HRP system is, indeed, greater than the pressure in the inlet pipe. The graph at **5(b)** indicates an outlet pressure range of 2.053 to 2.057 Bar, with a flow rate of 0.0362 kg/s. The maximum efficiency recorded is 68.61%, which is comparable to the peak delivery flow rate, Q_d, at the input elevation above the pump (2.5 meters) of 0.017 kg/s [12]. The pump achieves ideal efficiency within waste valve heights of 11 cm to 17 cm, with a height of 12 cm resulting in a maximized outlet flow rate and an efficiency of 68.61%.

This is due to more rate of delivery flow in comparison to the rest TRs. The pump's ability to raise water to a greater elevation is made possible by this pressure differential, which is essential to its operation. A tiny amount of water is forced through the exit pipe and raised to a higher elevation by the pressure surge. The outlet pipe's pressure rises as a result of this elevation gain. A waste valve eventually opens when the pressure in the outlet pipe builds, allowing the extra water and pressure to be released back into the primary water body or a secondary reservoir.

The final Rig has been prepared on the basis of Table 9 with the optimised WVH parameter as shown below.

Table 9. Optimum Parameters of WVH Vs Efficiency

Parameters	Optimum Parameter (m)	Waste Flow (Q_w)kg/s	Outlet Flow(Q_d)kg/s	(%) Optimum Efficiency
WVH	0.12	0.0569	0.0362	68.61
PCH	0.47	0.0755	0.0489	69.37
HD	0.17	0.0511	0.0399	77.37

The Optimum WVH was found to be 0.12m with delivery flow rate of 0.0362 kg/s, waste flow of 0.0569 kg/s.

3.1 Results and Discussion-Confirmatory Test

The theoretical pressures including static and surge pressures are considered for calculating the total pressures of the flow.

3.1.1. Static Pressure:

The static pressure in Figure 7 at point 2 is measured from the datum line which is kept at a level of 0.69 m from datum. The height of the free surface of the water in the storage tank from point 2 is 1.7 m. Therefore, the static pressure at point 2 is found to be 16677 Pa.

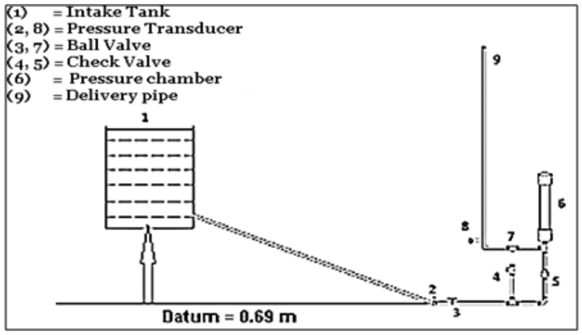

Fig 7. Static Pressure Head of TR

3.1.2. Theoretical Method

The pressure acts in the inlet and outlet is comprised of two components, i.e. due to the static pressure which is attained as a potential head and another component is due to formation of water hammer, which is the driving force acts on a HRP causing a huge pressure built-up also called pressure surge inside the piping.

The pressure surge, when the valve is closed suddenly and considering elastic model for PVC pipe, [13] which can be calculated as shown in **Eq. 10**.

$$P = V\sqrt{\frac{\rho}{\left(\frac{1}{K} + \frac{D}{Et}\right)}} \tag{10}$$

The pressure increases in elastic pipes after sudden closure of valve is given by where,

P = Pressure increases if the valve is shut suddenly.

ρ = Density of the flowing fluid (i.e. water)

D = Diameter of the flowing pipe,

E = Young's Modulus of the material of pipe,

Bulk Modulus of water $= 2.2 \times 10^9 Nm^{-2}$, Velocity of flow, $V = 0.293\frac{m}{s}$

Density of water, $\rho = 1000$ kg/m^3, Diameter of Pipe, $D = 0.0127\,m$, $E = 3.275 \times 10^9\ Pa$, Thickness of pipe, $t = 2mm = 2 \times 10^{-3}\ m$, now applying Eq.10, for PVC pipe, the pressure surge obtained is -

$$P_w = 189126 \text{ Pa} \tag{11}$$

Now static pressure, P_s = 16626 Pa and the total pressure $(P_s + P_w)$ is found to be 2.06 bar.

3.1.3. Experimental Method

The confirmatory experimental investigation was done by choosing a TR comprising of the resultant optimised parameters found from Table 9, with a) Waste valve height of 12 cm, b) Pressure chamber height of 47 and c) the horizontal distance between the pressure chamber and Waste Valve of 17 cm using DAQ system. The flow pattern was analysed since it is evident that the frequency of the HRP's valve movement increases with the waste valve diameter due to its reduction in the time intervals between consecutive movements [14]. The using pressure sensors readings are plotted in Figure 8(a) and 8(b). The final model has been tested with all the optimised parameters obtained from experimental studies. From Figure 8(b) and using interpolation method for pressure conversion (**Eq.7**) from mA to Bar, the outlet pressure is found to be 2.055 bar.

Table 10. Model Parameters of Optimised Test Rig

Parameters	Optimum Parameter	Optimum Efficiency (%)
Waste valve height (WVH)	0.12m	68.61
Pressure chamber height (PCH)	0.47 m	69.37
Distance between waste valve and pressure chamber (HD)	0.17 m	77.37

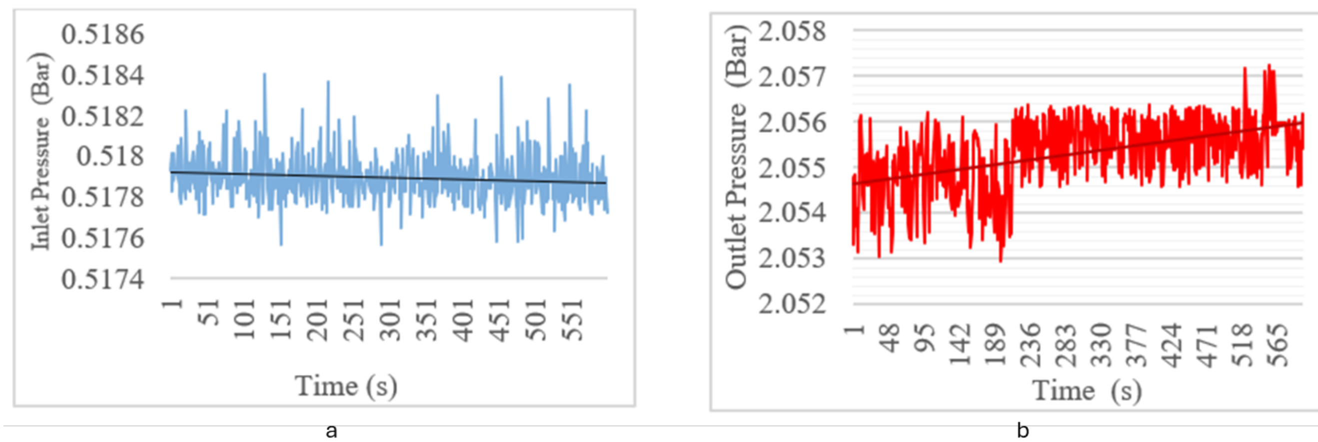

Fig 8. (a) Inlet Pressure for Confirmatory Experiment at Optimum WVH, PCH and HD, (b) Outlet Pressure for Confirmatory Experiment at Optimum WVH, PCH and HD

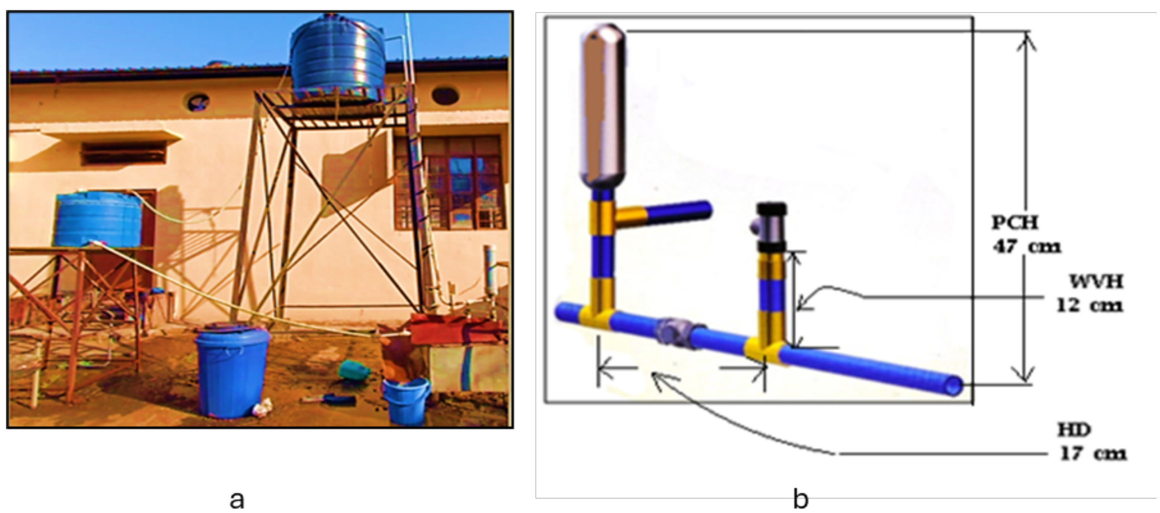

Fig 9. (a) The Enhanced setup, (b) The Final Test Rig

3.1.4. Comparative Analysis for WVH Variation

The comparative analysis of static pressure from **Eq. 9** and Water Hammer Pressure from **Eq. 11**, alongside the outlet experimental pressure measurements from Figure 5(b), is listed in Table 11 below. An extremely small average error level of 5.56E-04 is determined, suggesting that the validation was warranted as the height of the water column in the delivery pipe, the height of the supply tank, the height of the waste valve, and the duration of the waste valve stroke were found to influential [19,20].

3.1.5. Findings

The new design has successfully shown higher output as compared to the old model of hydrams. It resembles fully with the CFD analysis by (Shende et al.[15], Harith et al.[11] with their pressure distribution of 0.95×105 Pa and the pressure distribution obtained in this study is, $P = 1.38 \times 105$ Pa also comparable to the volume flow rate of $4.5238 \times 10 - 5$ m^3/s (162 l/hr.) in the drive pipe (L= 90 m) with a power output of 1.273 KW and efficiency of 57.3%, Mohammed[16]; Sutanto et al.[17] obtained the best efficiency of 57.3% on the length of the 8 meter input pipe. Table 9 presents the ultimate model, which incorporates the ideal parameter, with TR selected for optimization. During the confirmatory test in the experimental study, this model produced a flow rate of 143.64 L/hr, which was asserted to exceed 10% of the water elevation by harnessing the kinetic energy of the water

Table 11. Pressure measurement for WVH variation

Sl. No	1.P_s Bar	2.P_w Bar	3.Th.Pr. (1 + 2) Bar	4.Expt.Pr. Bar	5.Error(Diff) (3 - 4)Bar
1	1.66E-01	1.89	2.05626	2.0538200	2.44E-03
2	1.66E-01	1.89	2.05626	2.0522210	4.04E-03
3	1.66E-01	1.89	2.05626	2.0552002	1.06E-03
4	1.66E-01	1.89	2.05626	2.0520020	4.26E-03
5	1.66E-01	1.89	2.05626	2.0560030	2.57E-04
6	1.66E-01	1.89	2.05626	2.0564300	-1.70E-04
7	1.66E-01	1.89	2.05626	2.0553650	8.95E-04
8	1.66E-01	1.89	2.05626	2.0561240	1.36E-04
9	1.66E-01	1.89	2.05626	2.0573440	-1.08E-03
10	1.66E-01	1.89	2.05626	2.0562300	3.00E-05
11	1.66E-01	1.89	2.05626	2.0563234	-6.34E-05
12	1.66E-01	1.89	2.05626	2.0572643	-1.00E-03
13	1.66E-01	1.89	2.05626	2.0552365	1.02E-03
14	1.66E-01	1.89	2.05626	2.0562622	-2.20E-06
15	1.66E-01	1.89	2.05626	2.0552622	9.98E-04
16	1.66E-01	1.89	2.05626	2.0562622	-2.20E-06
17	1.66E-01	1.89	2.05626	2.0572621	-1.00E-03
18	1.66E-01	1.89	2.05626	2.0562344	2.56E-05
19	1.66E-01	1.89	2.05626	2.0559999	2.60E-04
20	1.66E-01	1.89	2.05626	2.0572344	-9.74E-04
Avg. Pr.	1.66E-01	1.89	2.05626	2.0557040	5.56E-04

flowing through a driver conduit [18]. This efficiency was comparable to 70.45% [5] and to the 93.14 L/hr efficiency recorded in another study [2], while maintaining a typical delivery pipe diameter approximately half that of the drive pipe diameter. This flow rate substantially exceeds the bulk flow rate of 30.24 liters per hour [19]. The implementation of newly designed parameters for the proposed model is justified, and the revised parameters attained in the Enhanced setup is illustrated in Figure 9(a) and the final constructed Test Rig presented in Figure 9(b) with a comparative efficiency table compiled by various researchers, as shown in Table 12.

Table 12. Efficiency Comparison of HRP

Name of Authors	(%) Efficiency	Name of Authors	(%) Efficiency
Asvapoositkul et al. [4]	68.0	Osome et al. [20]	54.0
Chatterjee et al. [19]	57.3	Matthias et al. [17]	44.0
Dhaiban [21]	29.0	Sampath et al. [?]	60.0
Diwan et al. [22]	31.1	Sarip et al. [23]	62.0
Harith et al. [11]	63.3		
Mohammed [24]	57.3		

3.1.6. Uncertainty Analysis of The Experimental Data:

The actual value is considered to lie within the uncertainty range of the measured value. Uncertainty analysis evaluates the influence of measurement uncertainty on the resultant calculation. Calibration, observation, and extended instrumental deterioration lead to measurement errors.

Any assessment of uncertainty is dependent on the pertinent equation(s). The analysis will underestimate the conclusion's uncertainty if the equations are inadequate and fail to incorporate all relevant factors, or if the component uncertainties are inaccurately minimized.

The experimental result R is determined by a data interpretation program (either manually or via computer) and is represented as R = R (x1, x2, x3,…, xN).

The root-sum square (RSS) method combines the effects of each input, and the RSS operation maintains the odds, so providing a reliable estimation of uncertainty in a calculated output [25]. If only a single measurement is conducted, the uncertainty in the experimental results is

$$\delta R_{xi} = \frac{\partial R}{\partial xi}\delta xi \tag{12}$$

If several independent variables are used,

$$\delta R = \sum_{i=1}^{N}\left\{\left(\frac{\partial R}{\partial xi}\partial xi\right)^2\right\}^{\frac{1}{2}} \tag{13}$$

Applying **Eqn. 12** into the D' Aubuisson Efficiency, (**Eqn.no 13**, the Relative Uncertainty, $\left(\frac{\delta\eta}{\eta}\right)$ can be propagated as,

$$\frac{\delta\eta}{\eta} = \sqrt{\left(\frac{\partial\eta}{\partial w}\frac{\delta w}{w}\right)^2 + \left(\frac{\partial\eta}{\partial W}\frac{\delta W}{W}\right)^2 + \left(\frac{\partial\eta}{\partial H}\frac{\delta H}{H}\right)^2 + \left(\frac{\partial\eta}{\partial h}\frac{\delta h}{h}\right)^2} \tag{14}$$

Now, finding partial derivative,

$$\frac{\partial\eta}{\partial w} = \frac{H\times W}{(w+W)^2\times h} \tag{15}$$

$$\frac{\partial\eta}{\partial W} = \frac{-H\times w}{(w+W)^2\times h} \tag{16}$$

$$\frac{\partial\eta}{\partial H} = \frac{w}{(W+w)\times h} \tag{17}$$

$$\frac{\partial\eta}{\partial h} = -\frac{H\times w}{(W+w)h^2} \tag{18}$$

and putting these values in **Eq. 14** above yielding, $\frac{\delta\eta}{\eta} =$

$$\sqrt{\left(\frac{H\times W}{(w+W)^2\times h}\frac{\delta w}{w}\right)^2 + \left(-\frac{H\times w}{(w+W)^2\times h}\frac{\delta W}{W}\right)^2 + \left(\frac{w}{(W+w)\times h}\frac{\delta H}{H}\right)^2 + \left(-\frac{H\times w}{(W+w)h^2}\frac{\delta h}{h}\right)^2} \tag{19}$$

The sensitivity coefficient for R is the partial derivative w.r.t Xi in **Equation 13**. This represents the essential equation of uncertainty analysis. The terms signify the influence of uncertainty in a singular variable (∂xi) on the overall uncertainty of the result (∂R). The partial derivative of R concerning xi, multiplied by its uncertainty range, remains consistent across all terms. The recognized levels of uncertainty employed by Rabha [26] in the present estimate are outlined in Table 13 below.

Table 13. Uncertainty Levels of selected parameters

Parameters	Uncertainty
Uncertainty in the lift height measurement, (m)	$\frac{\delta H}{H} = \pm 0.0005$
Uncertainty in the supply height measurement, (m)	$\frac{\delta h}{h} = \pm 0.0005$
Uncertainty in the lift water flow measurement, (kg/s)	$\frac{\delta w}{w} = \pm 0.001$
Uncertainty in the supply water flow measurement, W (kg/s)	$\frac{\delta W}{W} = \pm 0.001$

Now putting these values in **Eq. 19**, and using Table 11 for selecting the uncertainty levels, the % uncertainty for WVH variation has been calculated and presented in Table 14 (Using Table 15).

Table 14. % Uncertainty in WVH Variation

WVH variation:	% Uncertainty	Remark
17	4.88E-02	All the % uncertainty is substantially smaller than the primary value, indicating the result's legitimacy and dependability.
14	3.50E-02	
13	3.45E-02	
12	3.31E-02	
11	3.11E-02	

Table 15. Uncertainty Calculation Sheet for WVH Variation

WVH (cm)	Del. Flow (w)	Waste Flow (W)	Total (w + W)	$(w+W)\times 2$	$(w+W)\times 2h$	$(H\times W)$	(15)	Hxw	(16)	(17)	$(w+W)\times h$	$(w+W)h^2$	(18)	η_A (%)	Uncertainty	% Uncertainty
17	0.0239	0.0195	0.0434	1.88E-03	3.20E-03	0.0585	18.270	0.0717	22.392	0.3239	0.074	0.125	0.572	59.21	0.028901	4.88E-02
14	0.0305	0.0294	0.0599	3.59E-03	6.10E-03	0.0882	14.460	0.0915	15.001	0.300	0.102	0.173	0.529	59.56	0.020838	3.50E-02
13	0.0313	0.0283	0.0596	3.55E-03	6.04E-03	0.0849	14.059	0.0939	15.550	0.309	0.101	0.172	0.545	60.79	0.020966	3.45E-02
12	0.0362	0.0207	0.0569	3.24E-03	5.50E-03	0.0621	11.283	0.1086	19.731	0.374	0.097	0.164	0.660	68.61	0.022733	3.31E-02
11	0.0332	0.0402	0.0734	5.39E-03	9.16E-03	0.1206	13.168	0.0996	10.875	0.266	0.125	0.212	0.470	55	0.017080	3.11E-02

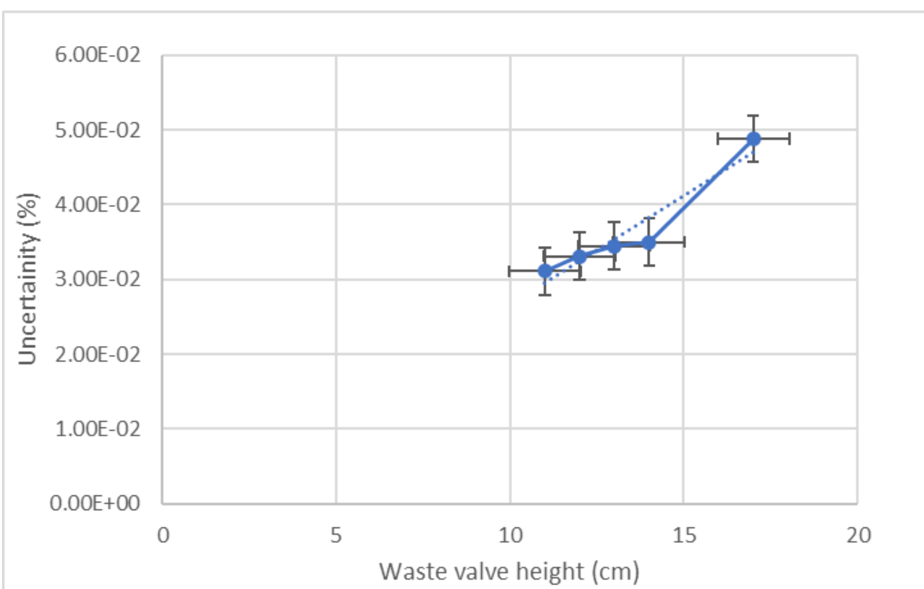

Fig 10. Uncertainty Calculation Sheet for WVH Variation

Because the experimentally observed values, which represent the percentage level of uncertainty, are exceptionally of a low range of 0.0488%, the error bars are considered to be almost unnoticeable, which is evidence of the high level of precision. This is illustrated in the graph that can be found in Figure 10. The following is an analysis of the data, taking into account the impact it has on the results: Assuming that the value that has been measured is 1000, the range of uncertainty will be $1000 \pm (0.0488\% \times 1000)$, which is equal to 1000 ± 0.4881000.

These ranges ensure that the error level is very minimal, i.e. the uncertainty is just ± 0.00488, making it nearly inconsequential. This indicates that the deviation is less than half a unit, demonstrating good precision. Furthermore, in this study, the chosen WVH ranges were 11-17 cm only, which ultimately demonstrate a minimal amount of inaccuracies.

4 Conclusion

The newly redesigned hydraulic ram pump (HRP) exhibits enhanced functionality and importance in transporting water to elevated sites without reliance on external power sources. By optimising characteristics such as waste valve height, the model improves overall D'Aubuisson efficiency, facilitating superior water supply with lower energy expenditure. This renders it exceptionally appropriate for rural and mountainous regions where electricity is limited or inconsistent. The enhanced design facilitates sustainable water lifting for irrigation, livestock, and residential purposes by harnessing the kinetic energy of flowing water. Moreover, the model facilitates minimal maintenance and long-term cost efficiency, hence solidifying the HRP's position as a reliable solution in decentralised water delivery systems. The redesign facilitates flexibility to various terrains and flow conditions, hence broadening the applicability of HRP in contemporary water resource management.

4.1 Future Scope:

Future innovations in hydraulic ram pump design should concentrate on enhancing efficiency, adaptability, and durability to improve performance and use. A crucial aspect is efficiency enhancement, wherein minimizing water wastage via optimal valve timing and augmenting delivery efficiency with updated pressure chamber designs can render the pump more effective. Adaptability and scalability can be enhanced by designing pumps that operate at reduced head heights and varying flow rates, so making them appropriate for a broader spectrum of situations. Furthermore, the enhancement of materials and durability can be achieved by the utilization of corrosion-resistant substances, such as composite plastics or stainless steel, alongside the incorporation of 3D-printed elements for economical production and maintenance. The integration of automation and intelligent monitoring, using IoT-based sensors for flow and pressure regulation, along with self-regulating valves, can significantly improve operating efficiency. An additional area for enhancement is the decrease of noise and stress, wherein sophisticated dampening devices could mitigate the effects of water hammer. The advancement of hybrid systems that integrate ram pumps with solar-powered auxiliary pumps, coupled with modular designs for enhanced adaptability, may broaden their use across various terrains and water supply requirements. By improving these aspects, future hydraulic ram pumps can achieve greater efficiency, reliability, and adaptability, thereby securing their ongoing contribution to sustainable water management.

It must be worth mentioning that since more water from the incoming water has been spilled out at the clack valve, hence, there are scope for further enhancement so as to achieve an ideal performance[21].

4.2 HRP Strengths:

A newly engineered hydraulic ram pump presents several significant advantages, rendering it an effective and sustainable water-pumping option. Its primary advantage is its exclusive reliance on the water hammer effect, necessitating no external power, electricity, or fuel, hence rendering it exceptionally energy-efficient and economically viable. Featuring few moving components, it is resilient, necessitates minimum upkeep, and can be fabricated from locally sourced materials, hence further decreasing expenses. Its eco-friendly characteristics, featuring zero carbon emissions and the absence of chemical usage, render it optimal for sustainable water management. The pump is especially designed for distant and off-grid areas, ensuring a dependable water supply for small towns, agricultural operations, and irrigation systems. A new design can boost performance by increasing efficiency, utilizing stronger yet lightweight materials, and accommodating lower head heights, hence increasing versatility across various applications. These advantages collectively guarantee that a hydraulic ram pump is a viable, economical, and durable solution for water pumping requirements.

4.3 HRP Weakness:

Creating and managing an experimental hydraulic ram pump test rig involves various issues that may affect results, system performance, and test configuration dependability.

The hydraulic ram pump's efficiency depends on precise input and output flow rates. Minor flow rate measurement inaccuracies can severely impact pump performance. The water Hammer Effect can surge system pressure. Due to pressure surge, serious pipe blast may occur. Maintaining uniform system pressure and flow, sealing all the joints and components are vital issue as it can impact efficiency calculations and produce inaccurate results.

Waste and delivery valves might be difficult to activate at the proper times and flow circumstances, causing uncontrolled mistakes during pump performance, cycle timing, and efficiency.

If the system is experiencing huge pressure built-up and sufficient pressure regulations not adhered into, it can damage equipment, and pressure sensors may not notice rapid pressure variations. Selecting the wrong dimensions during experimentation can lead to errors as it affects impulse force, reducing the water-lifting ability. If water supply is irregular or external variables like turbulence or air pockets disrupt testing flow, results will differ significantly.

4.4 Open Questions:

In the design of a hydraulic ram pump, numerous unresolved concerns persist owing to the intricacies of fluid dynamics, material constraints, and environmental variables. The unresolved inquiries encompass:

- Optimal Efficiency Limits - What is the theoretical maximum efficiency attainable by a hydraulic ram pump, and how can water wastage be mitigated without impairing functionality?
- Flow Rate Variability - What design strategies can be employed to enable a ram pump to function successfully amidst significant fluctuations in flow rates without necessitating manual adjustments?
- Low-Head Operation — Can a ram pump be engineered to operate efficiently with little elevation differentials, hence enhancing its applicability?
- Adapting Hydraulic Ram Pump Technology for Large-Scale Industrial or Municipal Water Supply Systems?
- Long-Term Durability of Contemporary Materials – What is the performance of modern, corrosion-resistant materials such as advanced composites or 3D-printed components under prolonged real-world conditions?
- Acoustic Disturbance and Structural Strain - Is it possible to substantially mitigate the water hammer effect without compromising pumping efficiency, and what are the most effective techniques to attenuate its effects on mechanical components?
- Automation and Smart Control - What methods can be employed to achieve automatic valve adjustments and IoT-based monitoring while maintaining the pump's simplicity and cost-effectiveness?
- Hybrid Energy Integration - Is it feasible to effectively integrate hydraulic ram pumps with alternative renewable energy sources, such as solar or wind, to enhance performance in low-head scenarios?
- Environmental Impact - What are the long-term effects of hydraulic ram pumps on local ecosystems, especially in tiny water bodies where flow diversion may influence aquatic organisms?
- Customizable and Modular Design - What is the most efficient modular design strategy that facilitates straightforward modifications and enhancements in response to diverse site conditions and water requirements?

4.5 Prospects and Recommendations:

It may assist rural populations in obtaining clean drinking water by abolishing manual water lifting and the use of hand pumps. The incorporation of micro-hydro power generation into renewable energy systems has demonstrated efficacy. Hydrams are an eco-friendly method for water pumping utilizing hydraulic power. Owing to their stability, adaptability, and ease of maintenance, as well as their ability to function without external energy sources, an HRP may emerge as a sustainable energy alternative in the future. These pumps can fulfil water pumping requirements in a cost-effective and sustainable manner as the world pursues environmentally friendly alternatives. HRP utilizes water sources efficiently and sustainably for fluid dynamics. They utilize the kinetic energy of water rather than electricity or any fuel source. This renders them suitable for remote or off-grid locations where traditional pumping systems are impractical or costly. The stability of Hydram and reliability ensure prolonged durability with minimal maintenance due to their limited number of moving components. These are appropriate for irrigation, livestock hydration, and rural water provision. The hydraulic ram pump is an environmentally sustainable, self-operating water-lifting device ideal for the Indian subcontinent, particularly in rural and hilly regions where electric and fuel-powered pumps are impractical. It has significant applications in irrigation, drinking water supply, and livestock hydration, making it an essential resource for small-scale farmers and remote communities. The future prospects of hydraulic ram pumps in India, Nepal, Bangladesh, and Sri Lanka appear bright due to escalating water shortages and the emphasis on ecological practices. Government initiatives promoting rural water management, along with economical local production, can enable widespread adoption. Implementing this technological initiative can enhance agricultural productivity and improve rural livelihoods.

5 NOMENCLATURE

Symbol	Description (Unit)	Abbreviation	
A	Cross-section of the pipe (m^2)	DAQ	Data Acquisition System
D	Diameter of drive pipe (m)	Diff.	Difference (in pressure)
d_1	Inner Diameter of Supply Tank (m)	Expt Pr.	Pressure obtained from Experimental Study (Bar)
D_i	Diameter of the drive pipe (m)	HD	Horizontal Distance between Waste Valve and Pressure Chamber
D_S	Supply pipe diameter (m)	HRP	Hydraulic ram pump
E	Young's Modulus of elasticity of material (Nm^{-2})	PC	Pressure Chamber
g	Acceleration due to gravity (m/s^2)	PCH	Pressure Chamber Height
h	Supply Head (m)		
H	Delivery head (m)	PVC	Polyvinyl chloride.
H_1	Inlet elevation above pump (m)		
H_S	Supply head (m)		
H_D	Delivery head (m)		
I	$Current, Ampere\ (A)$	**Greek Symbols**	
K	Bulk Modulus of elasticity of fluid $\left(Nm^{-2}\right)$	η_A	D'Aubuisson Efficiency (%)
kW	Kilo Watt	ρ	Fluid Density (kg/m^3)
L	Length of drive pipe (m)	∂xi	uncertainty in a single variable (x)
l	Litre	∂R	overall outcome uncertainty
L_S	Supply pipe length (m)	σc	Circumferential Stress (Nm^{-2})
m	Mass of flowing fluid (kg)	σl	Longitudinal Stress (Nm^{-2})
mA	Milli ampere (mA)		
P	Intensity of pressure wave $\left(Nm^{-2}\right)$		
P_s	Static pressure of HRP (Bar)		
P_w	Water hammer pressure of HRP (Bar)		
Q	Flow rate ((kg)/s)		
Q_d	Delivery flow rate (m^3/s)		
Q_1	Input water discharge (m^3/s)		
Qs	Supply flow rate (m^3/s)		
Q_w	Volume flow rate through Waste Valve (m^3/s)		
s	Unit of time (second)		
T	Time (s)		
t	Thickness of pipe (m)		
v	Velocity of flow $\left(ms^{-1}\right)$		
V_s	Volume of water supplied to HRP (L or m^3)		
W + w	Total mass flow supplied to HRP (kg/s)		
w	Delivery mass flow (kg/s)		

6 Acknowledgments

The Author is grateful to the Principal and Head of the Mechanical Engineering Department of Jorhat Engineering College, Assam, India. Also, indebted to the technical personnel for their help during the trial runs of the Test Rigs which was a stepping stone towards finishing this research works.

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