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Performance and Efficiency Study of Hydraulic Ram Pumps as an Alternative Solution for Water Supply in Remote Areas

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ABSTRACT
A hydraulic ram pump is a simple mechanical device that can pump water to higher elevations without using external energy such as electricity or fuel. This technology utilizes the kinetic energy of gravitational water flow to generate pressure through the water hammer effect. This article aims to examine the potential application of hydraulic ram pumps in water supply systems in remote areas and evaluate their efficiency and performance through analytical approaches and literature simulations. The analysis results indicate that hydraulic ram pump efficiency can reach 60–80% depending on the configuration and inlet flow rate. This pump is ideal for areas with a continuous flowing water source and a minimum elevation difference of 1 meter. This study is expected to provide a basis for the development of sustainable and energy-efficient water supply systems in areas with limited infrastructure.
Keywords: *hydraulic ram pump, hydro energy, water hammer, pump efficiency, rural water supply*

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I. INTRODUCTION

Providing clean water remains a major challenge in many parts of the world, particularly in rural and remote areas lacking adequate access to electricity grids and modern infrastructure. The need for clean water increases with population growth and the development of the agricultural sector, but energy constraints often hinder sustainable water distribution. In this context, hydraulic ram pumps, better known as hydram pumps, offer an attractive alternative solution, as this technology operates without the need for external energy sources such as electricity or fossil fuels. These pumps utilize only the potential energy of gravity-flowing water, providing a practical and sustainable solution for communities living in challenging geographic conditions such as hills and mountains [1].

Hydram pumps operate by exploiting a physical phenomenon known as water hammer, a sudden surge in pressure caused by the sudden interruption of water flow. This mechanism occurs when the pump's waste valve suddenly closes, increasing flow pressure and forcing some of the water into the air tank before being distributed to higher elevations through the pressure valve. This simple operating principle gives hydram pumps the advantages of minimal maintenance, low investment costs, and high durability due to their few moving parts. This technology is very suitable for application in areas that have continuous flowing water sources, such as small rivers or irrigation channels, and is able to serve household and agricultural water needs [2].

The efficiency of a hydraulic ram pump is highly dependent on several operational parameters, including water fall height, lift height, inlet flow rate, waste valve size, inlet pipe diameter, and air cylinder volume. Recent experimental studies have shown that variations in the dimensions of the waste valve and delivery valve can significantly impact pump efficiency. A configuration of a 2.75-inch waste valve diameter and a 2.2-inch delivery valve achieved the highest efficiency of 67.66% according to the D'Aubuisson method and 65.35% according to the Rankine method [1]. These results demonstrate that, despite the simple operating principle of a hydraulic ram pump, optimizing design parameters plays a crucial role in improving system performance.

Another study by Amanda and Fitria [2] also reported that the combination of a 1.5-inch inlet pipe diameter and a 4051 cm^3 air cylinder volume resulted in a pump efficiency of 89.41%, with an output flow rate of 0.0578 L/s at a lift height of 7.2 m. These results indicate that the air tube volume factor greatly influences pressure stability and water flow smoothness, thus affecting the amount of water that can be pumped to higher heights. Meanwhile, Nasution [3] showed that the length of the inlet pipe has a direct correlation with efficiency, where the highest efficiency of 44.7% was achieved at a low flow rate of 0.144 L/s, while higher flow rates actually reduced efficiency to 12.7%. This finding emphasizes the importance of considering the suitability between the inlet flow rate and pipe configuration in designing a hydraulic ram pump system.

In addition to valve and air tube dimensions, the design of the inlet and outlet pipes has also been shown to significantly impact pump performance. Jafri et al. [4], through another experimental study, highlighted that variations in valve height and inlet pipe diameter can result in drastically different efficiencies. In fact, under certain conditions, system efficiency can reach up to 95%, demonstrating the technology's significant potential for maximization. This aligns with research by Puspawan et al. [5], which states that optimizing the design of the air tube and waste valve can increase pumping capacity while maintaining flow stability. Therefore, further research into the interaction of various design parameters is essential to expand the use of hydraulic ram pumps in real-world conditions.

Although much research has been conducted, most previous studies have focused on single variables such as variations in pipe diameter or tube volume, while the interactions between parameters have often not been thoroughly investigated. Several recent studies have attempted to expand the scope of the study, for example by analyzing the effect of inlet angle on pump performance. Variations in specific inlet angles can affect efficiency, although these studies are still limited to laboratory simulations with constant flowrate and supply head conditions [6]. Thus, there is significant research opportunity to explore more complex combinations of variables, such as the relationship between variable supply head and fixed delivery head and inflow.

Beyond technical aspects, the existence of hydraulic ram pumps also has high social and environmental relevance. This technology supports the concept of sustainable development because it does not require external energy, thus reducing the community's dependence on fossil fuels and electricity infrastructure. Handayani et al. [7], in a case study in West Java, demonstrated that the implementation of hydraulic ram pumps can provide a water supply of up to 12 liters/minute at a delivery head of 12 meters with an efficiency of approximately 72%. These results demonstrate that simple technology such as hydraulic ram pumps can have a significant impact on rural communities in meeting their daily water needs at a low cost.

From this description, it is clear that hydraulic ram pumps have significant potential as an alternative solution for water supply in remote areas. However, there is still ample room for research development, particularly in optimizing operational parameters and implementing them in real-world conditions. Studies that focus on supply head as the independent variable, with delivery head and inlet flow maintained constant, can provide new insights into pump performance under the limited conditions often encountered in the field. This type of research is expected to address the practical needs of the community while also contributing academically to the development of appropriate, environmentally friendly and sustainable technology.

II. MATERIAL AND METHODS

This study uses an experimental approach with the aim of analyzing the performance of a hydraulic ram pump under conditions of a constant delivery head (Hd) of 10 m and a constant inlet discharge (Qs) of 100 L/minute, while the variable varied is the supply head (Hs) ranging from 1.5 m to 4.0 m. The choice of this experimental method is based on the need to obtain empirical data that can represent the real behavior of a hydraulic ram pump under certain operational conditions.

Materials and Equipment

The main material for this research is water as the working fluid, which is flowed through a hydraulic ram pump from a reservoir at a specific height according to variations in the supply head. Water was chosen because it is readily available, non-hazardous, and commonly used in hydraulic ram pump operations. The main equipment used in this research includes:

1. A laboratory-scale hydraulic ram pump designed according to hydraulic research standards with an inlet pipe (drive pipe) and an outlet pipe (delivery pipe).
2. A water reservoir as the reservoir source whose height can be adjusted to produce variations in the supply head.
3. A digital flowmeter to measure the inlet flow rate (Qs) and outlet flow rate (Qd) with high accuracy.
4. A manometer to measure the pressure in the pump section and ensure a constant delivery head of 10 m.
5. A stopwatch to measure the volumetric flow rate if data verification is required.
6. A data logger to ensure continuous and accurate data collection.

The selection of this equipment follows best practices in experimental hydraulic research, where the accuracy of flowrate and pressure measurements is crucial for the quality of the data obtained.

Research Procedure

The research phase began with the preparation of the hydraulic ram pump system. The reservoir was placed at an adjustable height to generate varying supply head (Hs). The delivery head (Hd) was maintained at 10 m using a delivery pipe whose length was varied as needed. The inlet flow (Qs) was maintained at 100 L/min using a control valve, which was adjusted at the beginning of the test.

Each supply head variation was tested repeatedly three times to obtain the average discharge value (Qd). The test results were then recorded in a research table. The hydram efficiency value was calculated using the equation:

$$\eta = \frac{Q_d \ x \ H_d}{Q_s \ x \ H_s} \ x \ 100\% \quad \text{.......} \quad (1)$$

Where Qd is the discharge outlet (L/min), Hd is the delivery head (m), Qs is the inlet discharge (L/min), and Hs is the supply head (m). This equation is in accordance with the hydraulic ram pump performance analysis method used in previous studies.

III. RESULTS

Research data shows that under conditions of a constant delivery head of 10 m and a constant inlet flow rate of 100 L/min, variations in the supply head (Hs) significantly affect the outlet flow rate (Qd) and the efficiency of the hydraulic ram pump. Experimental results show that the outlet flow rate increases with increasing supply head. At a supply head of 1.5 m, the outlet flow rate was recorded at 6 L/min, while at a supply head of 4 m, the outlet flow rate reached 15 L/min. This indicates that the potential energy of the water level plays a significant role in determining the pump's ability to push water to higher heights.

Figure 1 shows a nearly linear relationship between supply head and outlet flow rate over the test range. Increasing the supply head from 1.5 m to 2.5 m resulted in a significant increase in outlet flow rate, from 6 L/min to 10 L/min. However, at higher supply heads (3–4 m), the rate of increase in outlet flow rate tended to decrease. This phenomenon can be explained that although potential energy increases with increasing supply head, some energy is also lost due to fluid friction, turbulence, and the working characteristics of the hydraulic ram pump valve, so that not all energy can be converted into proportional discharge.

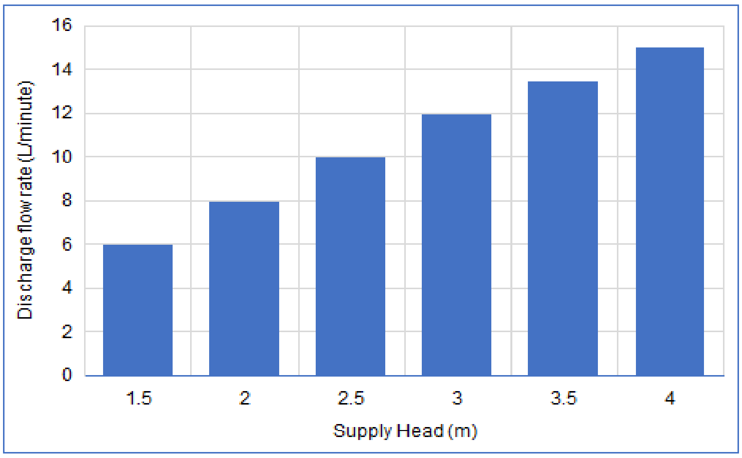

Figure 1. Relationship between supply head and discharge flow rate

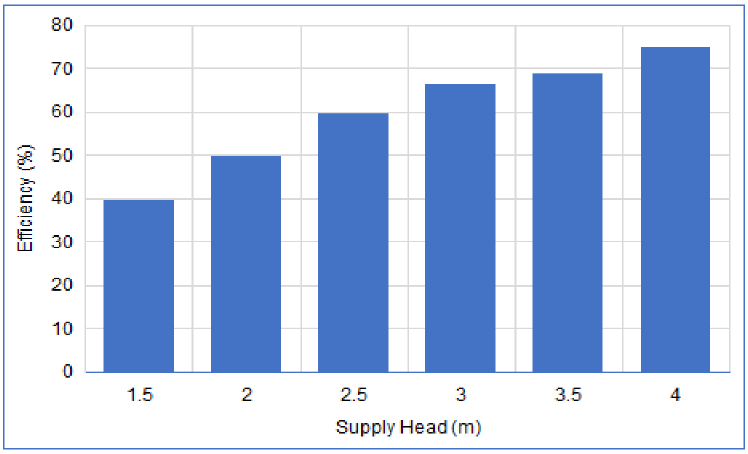

Figure 2. Relationship between supply head and efficiency

Furthermore, the efficiency of the hydraulic ram pump also increased with increasing supply head (Figure 2). At the lowest supply head (1.5 m), efficiency was recorded at 40%, while at the highest head (4 m), efficiency reached 75%. This indicates that the greater the supply head, the more energy can be utilized to overcome system losses, thus increasing efficiency. However, this pattern of efficiency increase is not entirely linear. At supply heads above 3.5 m, efficiency increases begin to plateau, indicating a practical limit to the performance of the hydraulic ram pump.

This finding aligns with previous research, which found that hydraulic ram pump efficiency is significantly influenced by the ratio of supply head to delivery head. Under constant delivery head conditions, increasing supply head can improve pump performance, but excessive increases will result in reduced efficiency due to energy losses in the system. Therefore, in real-world applications, selecting the optimal supply head is crucial for hydraulic ram pumps to operate at high efficiency while producing sufficient output flow to meet user needs.

Overall, the results of this study confirm that increasing supply head increases the discharge and efficiency of hydraulic ram pumps, but with a tendency to reach saturation. Therefore, in the design and application of hydraulic ram pump systems, a balance between supply head, delivery head, and water discharge requirements must be considered to achieve optimal performance and sustainable hydropower utilization.

IV. DISCUSSION AND CONCLUSION

Based on the results of research on the performance of a hydraulic ram pump under conditions of a constant delivery head of 10 m and a constant inlet flow rate of 100 L/minute, several important conclusions can be drawn:

1. Supply head significantly influences the outlet flow rate of a hydraulic ram pump. As the supply head increases, the outlet flow rate increases, from 6 L/minute at Hs = 1.5 m to 15 L/minute at Hs = 4 m. This indicates that the potential energy of the water flow significantly determines the pump's ability to propel water to higher heights.
2. Hydraulic ram pump efficiency increases with increasing supply head. Efficiency rises from 40% at Hs = 1.5 m to 75% at Hs = 4 m. However, the increase in efficiency is not linear, but tends to plateau at higher supply heads.
3. There is a tendency toward an optimum efficiency point. Although increasing supply head improves pump performance, at a certain point the efficiency increase becomes less significant due to energy losses such as fluid friction, turbulence, and valve characteristics.
4. Practical implications. Selecting the right supply head is very important in the design and application of hydraulic ram pumps to obtain a balance between adequate discharge and optimal efficiency, so that it can support the use of environmentally friendly and sustainable water energy.

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