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Predicting the Output of a Hydraulic Ram Pump

Krishpersad Manohar[1*], Anthony Ademola Adeyanju[1] and Kureem Vialva[1]

[1]Department of Mechanical and Manufacturing Engineering, The University of the West Indies, St. Augustine, Trinidad, West Indies.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The use of the hydraulic ram pump has been an attractive alternative in many areas in developing countries and rural areas that do not have or are located far from a reliable source of electricity. However, predicting the actual output delivery of the hydraulic ram pump poses many challenges due to the basic principle on which the hydraulic ram pump operates, the system design that consists of three pipes of different lengths, different diameters in each section and different Darcy-Weisbach friction factors. Based on experimental data, an empirical correlation was developed to predict the delivery output of a hydraulic ram pump for any combination of input and output head height. The accuracy of the predicted theoretical output flow rate was measured against the experimental data. The empirical correlation predicted the output flow rate within ±12% for any combination of input and output head height.

Keywords: Hydraulic ram; water pump; pump delivery; pump design.

1. INTRODUCTION

The first reported the working design of the hydraulic ram pump was built by John Whitehurst in 1775 [1]. Following this, the attractive feature of being able to pump water to a higher elevation without the use of any external energy source has encouraged many researchers to enhance

**Corresponding author: E-mail: krishpersad.manohar@sta.uwi.edu;*

the working concept and improve the efficiency of the pump. However, the hydraulic ram pump, due to the nature of the operation, still has low efficiency. Generally, for every 30L of water passing through the ram, the delivery output is the only 4L of water [2]. The advantage is that a well-designed pump can achieve a delivery output head often the input head [3].

The use of the hydraulic ram pump has been very attractive in many areas in developing countries and rural areas that do not have or are located far from a reliable source of electricity. Under these circumstances, the hydraulic ram pump can serve as an effective means of pumping water to a higher altitude, where it is needed, once a reliable water source is available [4]. This source could be a river, streams, spring, wells, dam ponds, and even some lakes. Essentially, once a steady flow can be created, the pump can operate, however, the source must provide a reliable supply of water [5]. Ideally, the ram pump is installed at a location lower than the water source that is used to create the flow head, hence, giving the fluid (water) some velocity [6].

However, predicting the actual output delivery of the hydraulic ram pump poses many challenges. This is due to the fact the basic principle on which the hydraulic ram pump operates use the sudden pressure fluctuations that occur when the moving fluid stops or changes direction [5]. This is compounded by the system design that consists of three pipes of different lengths, different diameters and different Darcy-Weisbach friction factors [7]. Also, in practice, the quality of the valves and the pipe used to influence the actual delivery output. Modelling the exact solutions for pressure surges in a three-reservoir conventional water hammer system can indicate the delivery output [8]. However, the calculations can be significantly warped due to the many interrelated practical parameters [8]. In this study, an empirical correlation was developed to predict the actual delivery output of a hydraulic ram pump with variation in input water head and output delivery height.

2. PUMP DESIGN AND CONSTRUCTION

A low-cost hydraulic ram pump was designed using readily available material. The majority of the pump construction used standard size PVC fittings. The one-way stop valves were standard size 32mm swing valves of brass construction. The valves were arranged such that when one closes the other opened and vice-versa. To control the water entering the body of the pump a 19mm PVC ball valve was installed along the 19mm inlet section. This valve also allowed and facilitated the priming of the pump. The main section of the pump was constructed using a 32mm diameter PVC pipe. Another 13mm PVC ball valve was placed on the outlet pipe of the pump to prevent back-flow and drainage of the supplied water when the pump was not operating. Fig. 1 shows a schematic of the main components of the hydraulic ram pump design and components arrangement.

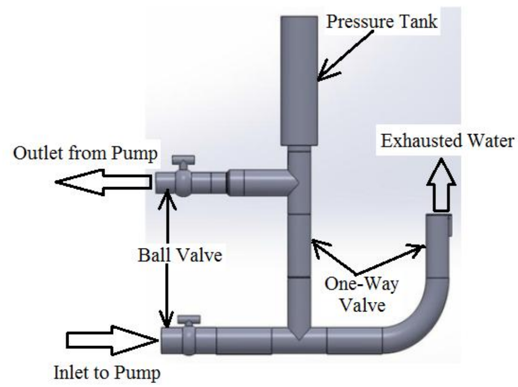

Fig. 1. Schematic of the hydraulic ram pump

Standard size 75 mm diameter PVC pipe, 127mm long, was used to construct the pressure tank. For the pressure tank, a standard size PVC end cap for the 75 mm diameter pipe was used on one end and reduction PVC fittings on the other end to facilitate attachment to the 32mm diameter pipe. Fig. 2 is a picture showing an exploded view of the pump components in the position for assembly.

Fig. 2. Exploded view picture of pump components

Table 1. Experimental pump supply water flow rate variation with input head height

	Pump outlet head (cm)									
	60	120	180	240	300	360	420	480	540	600
Input head (cm)	**Pump supply water flow rate (ml/min)**									
30	3600	2700	1500	700	0	0	0	0	0	0
60	5600	4800	3800	2700	2000	1300	600	0	0	0
90	7000	6800	6000	4800	4200	3100	2200	1500	800	0
120	8000	7800	6600	5200	4500	4000	3200	2500	1900	1300
150	8800	8400	8200	5600	4900	4400	4000	3000	2400	1700

3. EXPERIMENTAL SET-UP

An adjustable delivery head and input head system was designed for testing the hydraulic ram pump. The continuous flow water supply was from a 5000L storage tank. A float was incorporated in the constant head supply tank to maintain a constant supply head to the inlet of the pump. Different lengths of 13mm diameter PVC pipe was used to vary the delivery head. Fig. 3 shows a schematic of the experimental apparatus.

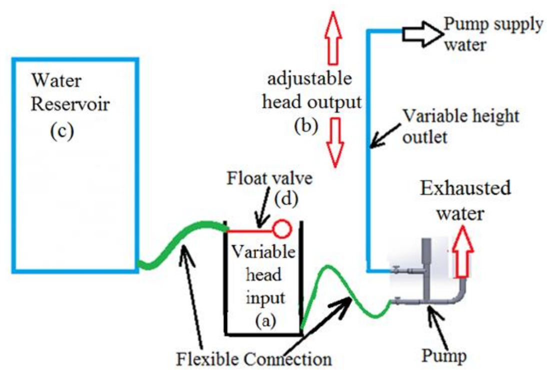

Fig. 3. Schematic of the experimental set-up for testing the hydraulic ram pump

During operation, the water delivered by the pump was collected at fixed time intervals. The delivered volume was measured with a 2000 ml measuring cylinder with an accuracy of $\pm$20 ml to determine the pump delivery output. The pump exhaust water was also collected at the same fixed time interval. The exhaust water volume was also measured with a 2000 ml measuring cylinder with an accuracy of $\pm$20 ml to determine the pump water flow rate.

4. EXPERIMENTAL RESULTS

The input head from the supply tank was varied between 30 cm to 150 cm in increments of 30 cm intervals. For each corresponding input head, the pump supply head height was varied between 60cm to 600cm in increments of 60cm intervals. Ten experiments were conducted for each test configuration and ten respective samples of pump supply water were collected. The supply water samples were collected for the 30s in each case. The recorded supply water volume flow rate listed in Table 1 is the average volume flow rate calculated from the ten samples for each data set. This procedure was repeated for each combination of input head and supply head.

5. ANALYSIS

The experimental data of pump supply flow rate was plotted concerning input head as shown in Fig. 4.

The Method of Least Squares was used to determine the best fit curve for each set of data. The trend observed was a general shape second-order polynomial curve. In each case, the regression analysis best fit curve for each set of data was plotted in Fig. 4. The respective second-order equation derived for each data set is listed below. The equations in this form showed that the pump supply flow rate, *y,* as the predicted variable corresponding to the input head as the known *x* variable.

60 cm outlet head: $y = -0.2222x^2 + 82.667x + 1360$ (1)

120 cm outlet head: $y = -0.3175x^2 + 105.14x - 220$ (2)

180 cm outlet head: $y = -0.2857x^2 + 107.43x - 1680$ (3)

240 cm outlet head: $y = -0.3889x^2 + 111.00x - 2340$ (4)

300 cm outlet head: $y = -0.3651x^2 + 106.38x - 2940$ (5)

360 cm outlet head: $y = -0.4722x^2 + 136.17x - 5435$ (6)

420 cm outlet head: $y = -0.2444x^2 + 91.6x - 4228$ (7)

480 cm outlet head: $y = -0.1944x^2 + 71.833x - 3405$ (8)

540 cm outlet head: $y = -0.3889x^2 + 121.67x - 7100$ (9)

600 cm outlet head: $y = -0.5556x^2 + 163.33x - 9800$ (10)

Analysing the constants associated with the regression analysis equations over the range of outlet head showed a linear trend. Using the method of least squares with the coefficient for the respective x^2, x and constant terms from equations (1) to (10), the data was plotted with the corresponding best fit line as shown in Figs. 5 to 7. Using the Method of Lease Squares the respective best fit linear equation was derived for each data set as shown in equations (11) to (13).

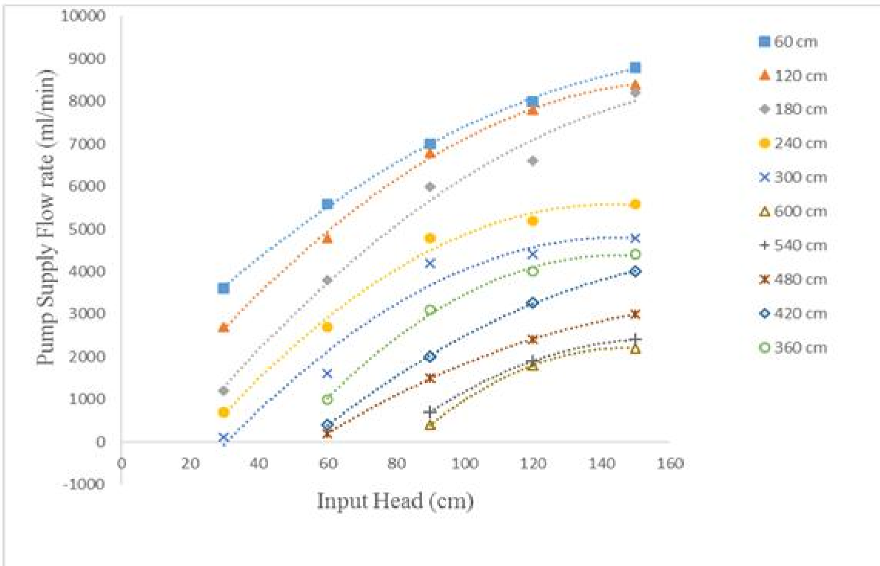

Fig. 4. Plot and least squares best fit line for pump supply flow rate vs. input head

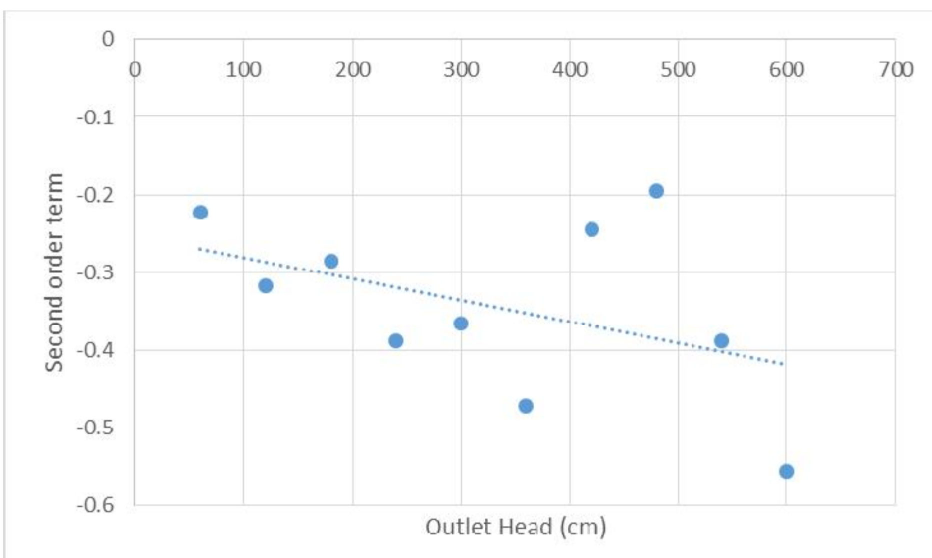

Fig. 5. Variation of second-order coefficient with pump outlet head

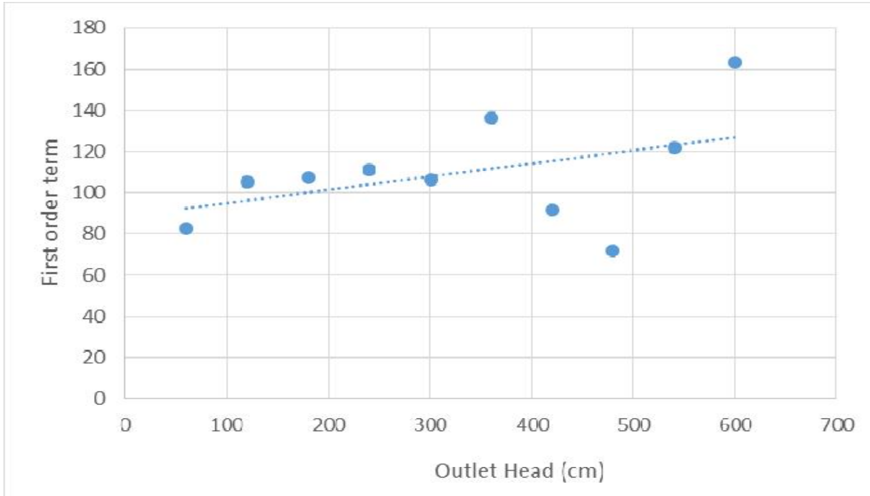

Fig. 6. Variation of first order coefficient with pump outlet head

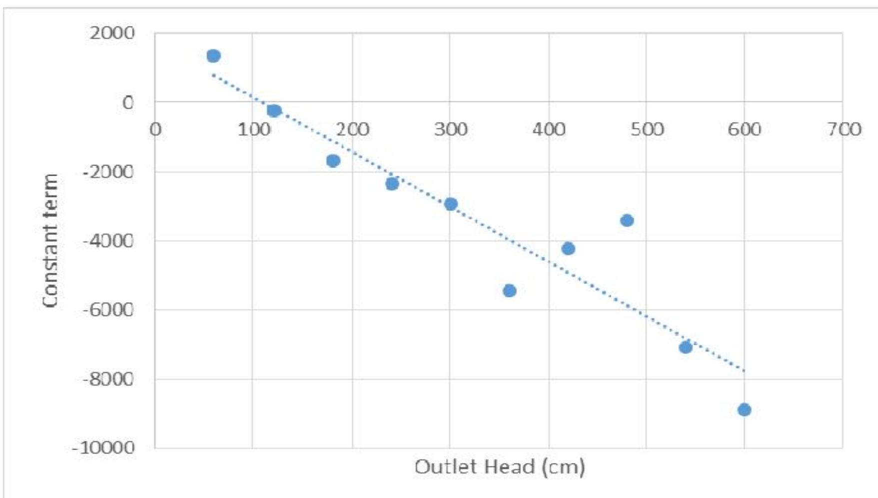

Fig. 7. Variation of constant term coefficient with pump outlet head

The equations in this form indicate the constant term, *b,* as the predicted variable corresponding to the outlet head as the known variable, *a,* for the respective x^2, x and constant term in equations (1) to (10).

Second order term: $b = -0.0003a - 0.2529$ (11)

First order term: $b = 0.0642a + 88.546$ (12)

Constant term: $b = -15.887a + 1754$ (13)

Combining the results from equations (11) to (13), an empirical correlation was developed to predict the pump supply flow rate for any combination of input head and output head for the hydraulic ram pump as presented in equation (14).

$$y = (-0.0003a - 0.2529)\,x^2 + (0.0642a + 88.546)\,x - 15.887a + 1754 \qquad (14)$$

In equation (14) the pump supply flow rate is represented by, *y*, the output head height is represented by, *a*, and the input head is represented by, *x*. The predicted delivery output for the hydraulic ram pump was calculated using the empirical correlation, equation (14), for the corresponding experimentally conditions. The percentage difference between the predicted theoretical pump delivery output and the experimentally measured output flow rate for the corresponding values were calculated. The results are shown on Table 2.

Table 2. Predicted delivery output water flow rate variation, [mL/min], with input head height and corresponding percentage difference from measured output water flow rate

Output Head, an Input (cm) / Head, *x* (cm)	60	120	180	240	300	360	420	480	540	600
30	3330 -8.1%	2735 1.3%	1621 7.5%	767 9.6%	0	0	0	0	0	0
60	5369 -4.3%	4582 -4.8%	3796 -0.1%	3009 10.3%	2222 10%	1435 9.4%	648 7.4%	0	0	0
90	6922 -1.1%	6170 -10.2%	5418 -10.7%	4665 -2.9%	3913 -7.3%	3161 1.9%	2408 8.6%	1656 9.4%	904 11.5%	0
120	7988 -0.1%	7237 -7.8%	6487 -1.7%	5737 9.4%	4987 11.8%	4237 5.6%	3487 5.9%	2736 8.6%	1986 4.3%	1236 -5.2%
150	8565 -2.7%	7785 -7.9%	7004 -17.1%	6224 10.0%	5444 11.8%	4663 5.6%	3883 -3.0%	3102 3.3%	2322 -3.4%	1541 -10.3%

6. DISCUSSION

Hydraulic ram pumps have been used for decades to pump water for agricultural application in rural areas. However, for design and application purposes, reliably predicting the output capabilities remain challenging due to the complex fluid dynamics associated with the three pipe flow system. This is compounded with the different pipe diameters in each section and the water hammer effect. The low cost experimental hydraulic ram pump was designed and built with standard material available in the average hardware store. The experimental set-up was designed to maintain a constant head supply at different set heights to ensure controlled input conditions.

A plot of the experimental data on Fig. 4 showed a second-order polynomial variation of the pump supply water flow rate with input head height variation. This trend indicated that the pump supply would increase with increasing input head and then level off at a maximum flow rate. Further increase of the input head above the optimum value would result in a negligible increase in output water flow rate. This trend was observed for the ten different output head height tested. Using the Method of Least Squares the best fit second-order polynomial equations (1) to (10) were obtained. From the equations, the coefficients associated with the second-order, first order and constant terms varied linearly for the range of output head height tested. From a plot of the respective coefficients in Figs. 5 to 7, the respective best fit linear equation was obtained.

Using the coefficients obtained from the best fit lines, an empirical correlation was developed to predict the output flow rate of the hydraulic ram pump for any combination of input and output head height. The accuracy of the predicted theoretical output flow rate of the hydraulic ram pump was measured against the experimental data. The predicted output flow rate of the hydraulic ram pump for the respective combination of input and output head was calculated and the results tabulated in Table 2. The percentage difference between the predicted and experimentally measured output flow rates (Table 1) was also calculated and listed in Table 2 at the corresponding points. Of the forty data points, the results from Table 2 showed that the experimentally measured output flow rates were within ±12% of the theoretically predicted output flow rate from the empirical correlation except for one data point that showed a deviation of -17.1%. This outlying test data point could be the result of experimental error in data collection.

7. CONCLUSION

- Predicting the output flow rate of a hydraulic ram pump remains challenging due to the complex fluid dynamics associated with the three pipe flow system.
- The hydraulic ram pump has a second-order polynomial variation of the pump supply water flow rate with input head height.
- The output flow rate of a hydraulic ram pump increase with the input head height to an optimum value.
- Further increase of the input head above the optimum value would result in a

negligible increase in output water flow rate.

- The empirical correlation developed predicted the output flow rate within ±12% for any combination of input and output head height.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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