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PERFORMANCE OF HYDRAULIC RAM BUILT WITH DIFFERENT VOLUMES OF AIR CHAMBER

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ABSTRACT

Electrical or fuel energy is usually required to drive a motor pump station in order to promote the mechanical elevation of surface water and groundwater. Therefore, this work aimed to evaluate and compare the hydraulic characteristics of a hydraulic ram built with different volumes of PVC air chambers, according to its efficiency and economy. Calibrated tanks and a stopwatch were used to obtain the supply flow, wasted water and repression volume. Four treatments were tested with 25% (125 L), 50% (250 L), 75% (375 L) and 100% (500 L) of raw material. PVC tubes of 10, 20, 30, 40 and 50 cm in length were used for treatments with different volumes of air chambers. The experiment was a completely randomized design. The analysis of variance, Pearson's correlation coefficient and the Tukey test for comparison among means were also performed. An increase in the repression volume and wasted water was observed when the volume of the air chamber increased. The 0.250 L air chamber presented better results for the repression volume variable. In addition, we could also verify an increase in performance of the hydraulic ram with increasing the volume of the air chamber.

Palavras-chave:
Rendimento
Irrigação
Martelo hidráulico
Energia sustentável

DESEMPENHO DE BOMBA HIDRÁULICA CONSTRUÍDA COM DIFERENTES VOLUMES DE CÂMARA DE AR

RESUMO

Energia elétrica ou de combustível é geralmente necessária para acionar uma estação de bomba motorizada, a fim de promover a elevação mecânica das águas superficiais e subterrâneas. Portanto, este trabalho teve como objetivo avaliar e comparar as características hidráulicas de um pistão hidráulico construído com diferentes volumes de câmaras de ar em PVC, de acordo com sua eficiência e economia. Tanques calibrados e cronômetro foram utilizados para obter a vazão de abastecimento, o desperdício de água e o volume de repressão. Inicialmente quatro tratamentos foram testados com 25% (125 L), 50% (250 L), 75% (375 L) e 100% (500 L) da capacidade do reservatório. Para os tratamentos com diferentes volumes de câmaras de ar, foram utilizados tubos de PVC com volumes de 0,050 L, 0,100 L, 0,150 L, 0,200 L e 0,250 L. O experimento teve o delineamento inteiramente casualizado, sendo realizada a análise de variância, coeficiente de correlação de Pearson e teste de Tukey para comparação entre médias. Houve um aumento na pressão e na quantidade de água desperdiçada quando o volume da câmara de ar aumentou. A câmara de ar de 0,250 L apresentou melhores resultados para a variável recalque. Além disso, foi observado que o aumento do volume da câmara de ar, proporcionou um aumento no desempenho da bomba hidráulica.

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INTRODUCTION

Water is an essential natural resource for life and indispensable for the development of daily activities. Although abundant, this natural resource is finite and poorly distributed. Population growth and industrial development have led to an increase in energy demand and water use, contributing to accelerate the depletion of non-renewable natural resources and compromising their natural replenishment capacity (PATHAK *et al*., 2016; MBIU *et al*., 2015).

At the same time, there is an increasing cost of electricity in water supply in the agricultural sector. Due to the lack of electrical energy in many areas and the threat of non-renewable resources scarcity, it is essential to seek alternatives to generate renewable and non-polluting energy (MAYOR, 2008).

Thus, there are simple and useful equipment that can provide an effective alternative to the problems of lack or scarcity, both in terms of electricity and resources (YOUNG, 1995). A viable alternative is the use of hydraulic ram, which is a kind of hydraulic pump that does not use electricity or fuel to operate. This equipment works 24 hours a day without harming the environment by using hydraulic energy. It is a device designed to raise water through its own energy, requiring no other types of supplementary energy (SENGUPTA; NARULA 2013).

Nevertheless, hydraulic ram is not used in large scale because its performance is limited. On the other hand, Confessor *et al*. (2016) reported that this type of pump has several applications for both the agricultural and urban environment, such as the capture of rainwater, rivers and streams, besides it can be used in places that are difficult to access and have low availability of electricity.

The hydraulic ram, like any machine, has disadvantages in its use. It produces noise resulting from water hammer; its functioning may be impaired due to suspended solids in the water; it needs a waterfall to work well; and only a portion of the water repressed from the available flow is used (HORNE; NEWMAN, 2000). According to Abate and Botrel (2002), local conditions are also a determining factor for the hydraulic ram performance.

A hydraulic ram pumping system consists in a header tank, a delivery pipe, waste and delivery valves, an air chamber and a drive pipe. The function of the air chamber is to store water at the discharge pressure between water hammer and absorb the impact of the pumping (YOUNG, 1995).

The water that reaches the hydraulic ram is initially poured through the waste valve until it reaches enough speed for the valve to close, abruptly interrupting the discharged water (water hammer) (JENNINGS, 1996). This abrupt interruption of the water flow causes an overpressure that spreads in a wave form through the pipe, which allows the elevation of a portion of water that had penetrated the machine. A check valve (delivery valve) prevents the raised portion of water from returning to the hydraulic ram, making it a cyclical phenomenon (HUSSIN *et al*., 2017).

For the pump operation, the difference in level or fall that can be used to activate the system must not be less than 1 m, and the drive pipe must be straight and have a diameter larger than the outlet piping diameter (NETTO *et al*., 1998). The ram efficiency varies between 20 and 70%, according to the head ratio of delivery head (H_d) and supply head (H_s), so H_d / H_s.

Therefore, there is a noticeable demand for low-cost, easy handling and efficient technologies in many farms. In addition, studies are required to improve the performance of the hydraulic ram to propose constructive features that quantify its efficiency and promote its applicability in the agricultural environment.

Thus, this research aimed to evaluate and compare the hydraulic characteristics of a hydraulic ram built with different volumes of PVC air chambers, according to its performance and economy.

MATERIAL AND METHODS

The experiment was performed from November 2017 to February 2018 at the Federal Rural University of the Amazon - Campus Capitão Poço - Pará, Brazil, in the micro region of Guamá, located 226 km from the city of Belém (01º44’47’’S and 47º03’34’’W and elevation 73 m).

Hydraulic ram building and testing parameters

The methodology presented by Abate and Botrel (2002) was used to assemble the hydraulic pump. We used similar pieces to those proposed by Cararo *et al*. (2007), following the guidelines of Filho (2002) to built the pump. Thus, the pump was made up of the following parts (Figure 1): 4 pipe nipples (1); 1 cap (2); 1 ball valve (3); 1 elbow (4); 2 threaded tee (5); 1 bushing with hose adapter (6); 1 metal vertical check valve which works as delivery valve (7); 1 metallic foot valve, that works as waste valve (8), included a 10 cm 5/16 bolt, 3 nuts, 1 washer and 1 spring; 2 short pipe adapters (9); and PVC pipes (10).

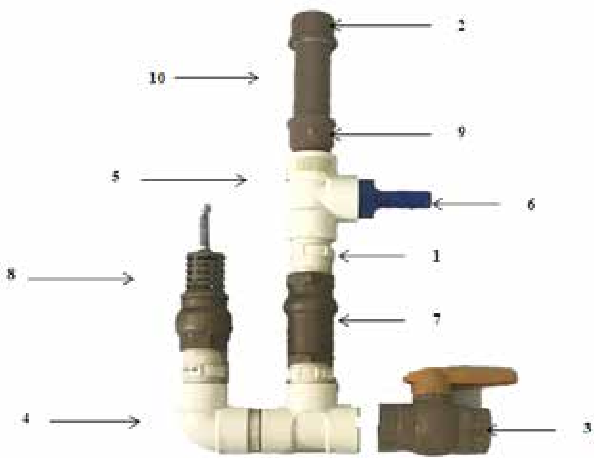

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Figure 1. Parts to build the hydraulic ram

A water tank with a capacity of 500 L (liters) was used as a supply tank. From the tank to the pump there were a 5-meter difference in level and 18 meters distance. The water flowed through an one inch PVC drive pipe, reduced to ½ inch in the delivery pipe (hose). Several supply flow tests were performed from different volumes of water in the tank. The same procedure was done with another calibrated tank with 50 L capacity. Initially, four treatments were performed with the supply tank capacity of 25 % (125 L), 50 % (250 L), 75 % (375 L) and 100 % (500 L). These tests corroborate with the premise that the larger the water column, the greater the pressure available to the system.

A stopwatch and two calibrated tanks with a capacity of 20 L were used to test the different air chambers volumes of the hydraulic ram. Therefore, it was possible to obtain the repressed and wasted volume in the system. In addition, the number of valve beats of the hydraulic ram was counted, considering the same setting for all air chamber volumes. Thus, the treatments with the air chambers were respectively 0.050 L, 0.100 L, 0.150 L, 0.200 L and 0.250 L (Figure 2).

The efficiency of the hydraulic ram was determined by Equation 1 using the variables: (1) repression, (2) supply (repression + waste), (3) lift elevation (delivery head) and (4) fall elevation (supply head). The flow rate ratio was calculated by the difference between supply and repression (YOUNG, 1995).

$$\eta = \frac{Q_{out}\, H_d}{Q_{in}\, H_s}\ .100 \quad (1)$$

Where:

η = Hydraulic ram efficiency (%);

Q_{out} = Volumetric flow rate at the outlet ($m^3\ s^{-1}$);

H_d = Delivery head (m);

Q_{in} = Volumetric flow rate at the inlet ($m^3\ s^{-1}$);

H_s = Supply head (m).

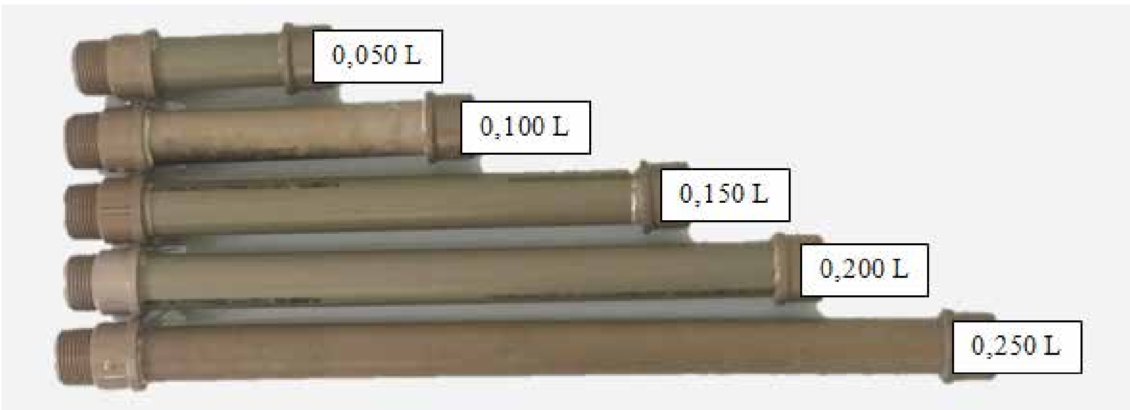

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Figure 2. PVC air chamber used in the experiment

Experimental design

The experiment was performed in a completely randomized design (CRD). Statistical analyses were performed on the repression volume, wasted water, number of valve beats and efficiency, being evaluated with the Anderson and Darling Test (1952) to verify the normality of the data ($p < 0.05$). Then, the analysis of variance (ANOVA) was performed by the F test (Fisher - Snedecor) for the variables that presented normality, with a significance level of 5%.

The Tukey's honestly significant difference (HSD) test was performed with a significance level of 1% for the variables that presented a difference by the F test. Analysis of variance were performed for the different flows (0.050 L, 0.100 L, 0.150 L, 0.200 L and 0.250 L), in order to observe the behavior by simple linear regression. Based on the analysis of variance applied to the regression, scatter plots were generated, where the air chambers volumes was the independent variable, and the repression volume, wasted water, number of valve beats, and efficiency were the dependent variables.

Pearson's correlation coefficient was also applied to verify the similarity between the variables. All statistical analyses were processed by the software SISVAR (FERREIRA, 2003) and AgroEstat (BARBOSA and MALDONADO JÚNIOR, 2010).

RESULTS AND DISCUSSION

Regarding the tests performed with different water levels in the tank, we can observe a significant difference between the treatments at 25%, 50%, 75% and 100 % (Table 1).

The tests performed according to the capacity of the tank aimed to evaluate the moment when a greater amount of water will be available in the system through the supply flow. The tests on the tank were performed without the hydraulic ram pump to quantify only the initial volume. However, it would be necessary to work with the tank level close to its maximum limit and with few variations in the water volume in order to obtain good accuracy in the tests with the different volumes of air chambers. The behavior of the treatments in response to the flow variable is demonstrated by the Tukey (1953) test in Figure 3.

Through the analysis of variance, we can observe that the linear and quadratic (second degree polynomial) regression models showed significant differences in the air chambers. Then, the result of the mean square of the analysis of variance is observed for regression in function of the variables (repression volume, wasted water, number of valve beats and efficiency) (Table 2). The study performed by Inthachot *et al*. (2015) demonstrated that there was no significant difference in efficiency of the hydraulic ram when operated with the large (3.6 L) and medium size (2.3 L) pressure chamber (33.1% and 32.6%, respectively).

The result of the regression in the analysis of variance for efficiency is shown in Table 2. We can verify that there was no significance for the quadratic regression, but it could be observed in the first degree model. Thus, the most suitable model is linear, at the 1% probability level. In addition, there was a relevant coefficient of variation of 4.48% (Table 2).

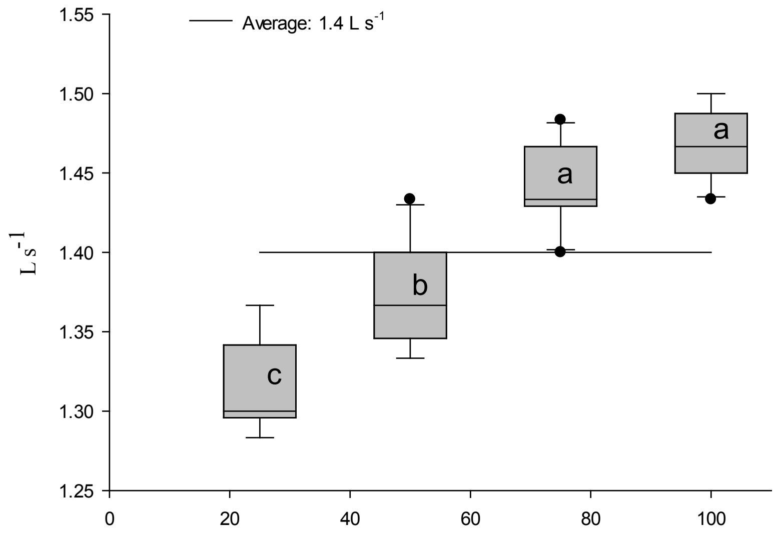
The variable number of valve beats presented significant linear regression at the level of probability of 1% by the F test. However, when analyzing the volume variables of repression and wasted water, we can observe significance in the linear and quadratic models. In addition, the coefficients of variation (CV%) for each variable showed great precision in the experiment.

The results obtained by the Tukey test corroborate with the Stevin's theorem which affirm that the larger the water column in the tank, the greater the pressure at the outlet of the drive pipe. This increase in pressure also provides an increase in the flow that will supply the system. However, it was observed that there was no significant difference between the levels of 100% and 75%, so this little variation did not compromise the tests with the air chambers (Figure 3). Thus, to obtain a greater supply flow, the tank level was kept close to its maximum capacity.

Table 1. Analysis of variance for treatments with different capacity for water volumes in the supply tank

Source of variation	DF	Sum of Squares	Mean square	Value F	P-value
Tank Capacity	3	0.077	0.025	33.22**	0.00
Error	36	0.027	0.0007		

Note: DF, degrees of freedom; ** Significant at the 1% probability level by the F test; NS not significant



Note: Means followed by different letters differed by the Tukey test at the 1% probability level

Figure 3. Means of treatments with different capacity of water volumes in the supply tank

Table 2. Mean square of the analysis of variance applied to the regression as function of the variables (repression volume, wasted water, number of valve beats and efficiency)

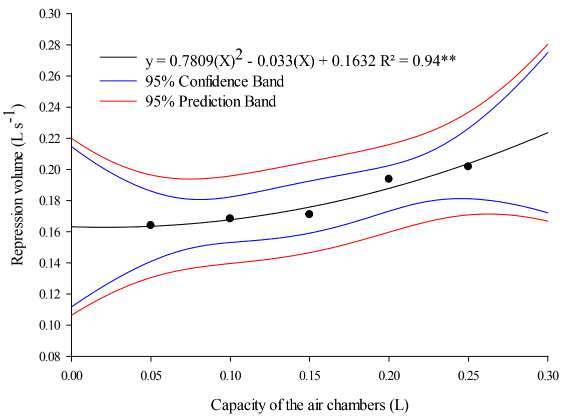
Source of variation	DF	Mean square			
		Repression volume	Wasted Water	Number of valve beats	Efficiency
Linear regression	1	0.01**	0.006**	392.04**	394.00**
Quadratic regression	1	0.0005**	0.0008**	0.25^{NS}	1.64^{NS}
Deviation	2	0.0003**	0.000007^{NS}	6.79**	16.34**
Error	45	0.00002	0.0001	0.74	5.19
Air chambers	4	0.002**	0.001**	101.47**	107.08**
Error	45	0.0002	0.0001	0.74	5.19
CV (%)		2.65	3.90	3.21	4.48

** Significant at the 1% probability level by the F test; NS not significant; DF, degrees of freedom; CV, coefficient of variation.

Several factors must be identified for the selection of the hydraulic ram size (ABATE and BOTREL, 2002). In field conditions, the supply flow of a stream must be checked during the dry season, in order to verify that there will always be a supply to the system. However, it is possible to estimate that the supply flow during dry season is lower compared to the rainy season.

The more compact the hydraulic ram, eliminating knees and bent pipe, the lower the fluid load loss (FILHO, 2002). Rojas (2002) also recommends that the water flow should avoid bends, keeping as straight as possible to reduce load losses. In addition, the hydraulic ram has its load loss modified when the distance and height of the volume to be repressed are increased. However, for this experiment, the impulse valve was in a vertical position in order to facilitate the adjustment of the screw and capture the wasted water, without compromising the results.

From the regression analysis performed between the variables of repression volume (L s^{-1}) in response to the air chamber capacity, we can observe that the parable is positive second degree polynomial; which means that there is a trend to increase the repression volume when the air chamber volume is increased. In addition, according to the coefficient of determination (r^2), values close to 1 indicate that the proposed model is suitable to describe the phenomenon. Thus, the value of r^2 obtained is 94%; which means that the model is adequate (Figure 4).



** Significant at the 1% probability level by the F test

Figure 4. Repression volume (L s^{-1}) according to the different capacities of the PVC air chambers

The evaluation of the repression volume can be strongly related to the increase in the volume of the air chamber. According to Yong (1995) the air chamber has the function of compressing the air at the moment of the water hammer and then propelling the fluid into the delivery pipe. In addition, according to Cararo *et al*. (2007), the repressed volume may vary when the repression height difference is increased or decreased.

For the variable wasted volume (Figure 5), the mathematical model that best suited the test results was the quadratic model, which resulted in a coefficient of determination (r^2) of 0.99. The regression analysis for the wasted volume also shows that the best-fitting straight line is a positive second degree polynomial, an r^2 value of 99%. Therefore, the model is appropriate (Figure 5).

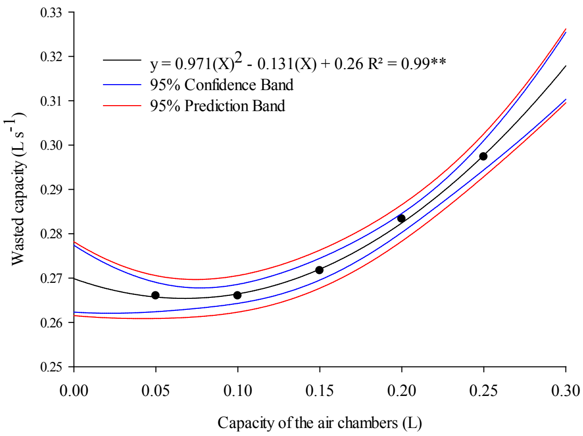


Figure 5. Capacity of the wasted volume (L s^{-1}) of the hydraulic ram as a function of the capacity of different volumes of the PVC air chambers. ** Significant at the 1% probability level by the F test

In the research performed by Horne and Newman (2000), they found that approximately 3/4 of the water that passes through the system comes out of the waste valve. Most of the water in the supply tank is directed to the waste valve. In field conditions, this portion of water that falls on the ground tends to evaporate (due to the temperature) or to infiltrate until it reaches the water table and, consequently, replenish the watercourses. However, Oliveira (2011) reported that it is necessary to seek more viable alternatives to avoid waste, considering that the water use is becoming increasingly restricted. To solve this problem, Dhaiban (2019) suggested techniques for building a system to collect and direct wastewater to the tank. With regard to the number of valve beats, a relationship inversely proportional to the volume of the air chamber was found. This can also be seen in Figure 6, with the result of the linear regression analysis for the number of valve beats.

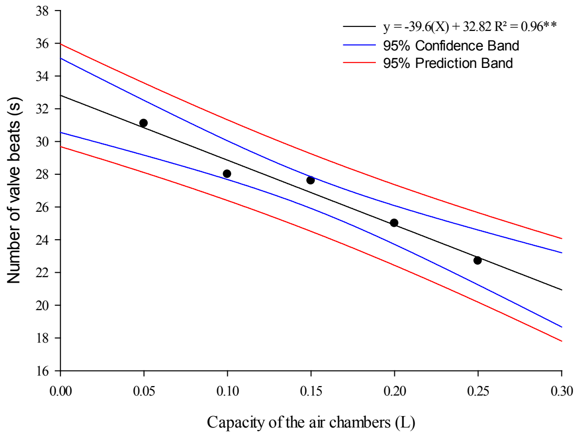


Figure 6. Number of valve beats of the hydraulic ram for different volumes of PVC air chambers. ** Significant at the 1% probability level by the F test

In Figure 6 we can observe that the straight line with a negative slope and a coefficient of determination (r^2) of 96% indicates a reduction in the number of valve beats as the air chamber volume increases. In addition, it is important to note that the adjustment of the moving parts located in the waste valve was the same for all experiments with air chambers.

Knowing that the number of valve beats that the hydraulic ram provides is due to water hammer on the waste valve, Cararo *et al*. (2007) observed that the variation of the beats can be justified due to the wear of moving parts or due to the increase in air chamber pressure. When testing the performance of the hydraulic ram pump, Mbiu (2015) reported that the valves were moving parts that required replacement due to the constant friction of the parts. Furthermore, the use of aluminum alloys to absorb most of the noise produced is recommended, since they are also good durability materials.

Abate and Botrel (2002) reported that lower beats per minute produce greater pressure in the pipeline and, consequently, present greater repression per beat. Jennings (1996) described that the cycle is repeated between 20 and 100 per minute, depending on the ratio between repression and supply flow. In addition, the number of cycles per minute is different for each hydraulic ram. For Young (1997) in a waste valve configuration, the frequency of beats depends only on length and height, not being influenced by the size of the pump. Inthachot *et al.* (2015) described that the hydraulic ram uses the kinetic energy of water flowing in a drive pipe to pump up about 10% of it to a higher elevation.

Considering that the variables obtained significant differences in relation to the increase in the air chambers, the Pearson correlation between variables was analyzed and the result is shown in Table 3.

Table 3. Pearson correlation coefficient between variables (repression volume, wasted water and number of valve beats)

Variables	Repression volume	Wasted water
Wasted water	0.71**	-
Number of valve beats	-0.84**	-0.67**

** Significant at the 1% probability level by the F test.

In Table 3 we can verify that the wasted volume correlated with the repression volume. A correlation coefficient of 0.716 demonstrates that the changes in one of the variables can modify the other, being a strong correlation. In summary, the increase in one variable is directly proportional to another. According to Callegari-Jacques (2003), a strong linear correlation between two variables has a coefficient between $0.6 < r_{xy} < 0.9$. Oliveira (2011) verified that the repression volume is associated with wasted water, establishing an average for tests in triplicates.

When analyzing the number of valve beats according to repression and waste, the correlation coefficients remained strong, however in a negative way (-0.844 and -0.679). Thus, the greater the repression volume and wasted water, the less number of valve beats the hydraulic ram pump will perform (Table 3).

Considering the positive proportional growth of the repression volume and wasted water variables, Oliveira (2011) evaluated the characteristics of an alternative hydraulic ram made with disposable PET bottles. The authors demonstrated the decrease in performance due to the increase in the volume of the air chamber from 0.6 L to 2 L. Air chambers with large volumes or inadequately designed for the system are not recommended, as they tend to decrease the efficiency of the pump (HUSSIN, 2017).

Regarding the assembly of the ram pump, Guo *et al*. (2018) proposed a method for the optimal design and performance analysis with numerical simulation to reduce discharge losses, increase efficiency and shorten the number of prototypes, and develop high-performance product. In this method, the valves become more easily controlled and regulated in the laboratory, as well as monitoring the flow of liquid inside the device and the pressure distribution.

From the specific analysis of each variable, the efficiency calculations of the hydraulic ram were performed. In Figure 7 is shown the result of the statistical analysis.

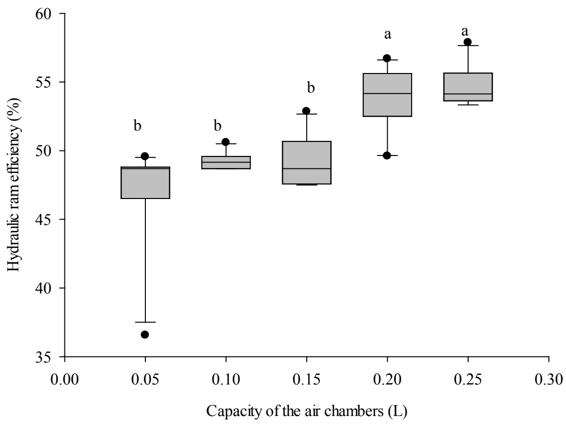


Figure 7. Boxplot with mean values of hydraulic ram efficiency (%) in PVC air chambers of different capacities. The means represented by different letters differ by the Tukey test at the 1% probability level. Coefficient of Variation = 4.48%

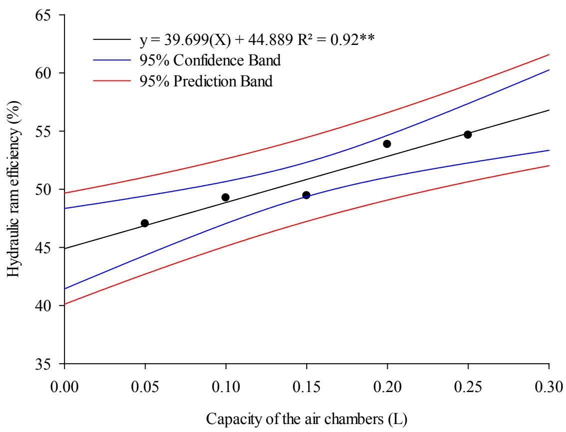
The efficiency of the hydraulic ram depends mainly on the difference in fall elevation between the supply tank (supply head) and the pump, the difference in lift elevation between the pump and the delivery head (eq. 1), and the accuracy in which the device is manufactured (ROJAS, 2002). Regarding the parameters for manufacturing the ram pump aiming at its greater efficiency, Sheikh *et al*. (2013) highlighted the drive pipe diameter, drive pipe length, flow discharge, pressure at waste valve, and head losses in the system. Pathak *et al*. (2016) and Mohammed (2007) reported that the development of a hydraulic ram pump would conveniently alleviate the problem of water supply to the mass populace. Therefore, different combinations of the supply and delivery heads and flows, length and weight of the impulse valve, length to diameter ratio of the drive pipe, volume of the air chamber and size of the valve are suggested to increase the performance of the device.

The hydraulic ram efficiency is not high since much of the water supplied is not repressed and also by the use of plastic parts, which cushion the water hammer (CARARO *et al.,* 2007). Gouvea *et al.* (2013) reported that the fire extinguisher pressure chamber (metallic) is more efficient compared to the hydraulic ram made of polyethylene terephthalate (PET).

In addition to these limitations, the hydraulic ram is also influenced by the head loss in the system, which also favors a decrease in efficiency. However, in the present work, it was not possible to estimate the head loss of the part that performs the water hammer, as it was modified.

Inthachota (2015) constructing a reliable and low cost raw, made of locally available PVC parts, observed that it is possible to maintain a good pump performance. This author mentioned that, when built in suitable sites and correctly installed, the pump can be used to irrigate certain crops. In addition, as for users introduced to the technique and device configuration, there should be no major difficulties in installation and maintenance.

The result of the linear regression analysis for efficiency, according to the types of air chamber volumes is presented in Figure 8.



**significant at the 1% probability level by the F test

Figure 8. Hydraulic ram efficiency (%) for different volumes of PVC air chambers

In Figure 8 we can observe that, when an increase in the air chamber occurs, the efficiency of the hydraulic ram is improved. The coefficient of determination also showed a reliable value, demonstrating that the linear model is suitable for the experiment. According to Kitani and Willardson (1984), the hydraulic ram has a maximum performance of 60% in terms of the amount of water transported, making it an extremely important factor for places with water scarcity.

Pathak *et al*. (2016) and Hussin *et al*. (2017) reported that the efficiency of the hydraulic ram is due to the presence of the valves and the air chamber in the system. As the pump operation is intermittent due to the cyclical opening and closing of the valves, an increase in the pressure of the transmission piping occurs. In addition, the presence of the air chamber will increase pressurization in the system. The water enters into the pressure chamber, which compresses the air until it can no longer be compressed. The pressure chamber pressurizes the water, causing it to flow into the delivery pipe.

CONCLUSION

- The outlet pressure in the drive pipe was directly influenced by the level of water column inside the tank, especially at 100% and 75% levels. We could observe an increase in the repression and wasted volumes when the volume of the air chamber was increased. In correlation with the variables, the repressed and wasted volumes had a strong positive correlation. On the other hand, the number of beats related to the other variables showed a strong negative correlation. The 0.250 L air chamber presented better results for the repression volume variable. In addition, we could also verify an increase in performance of the hydraulic ram with increasing the volume of the air chamber.

AUTHORSHIP CONTRIBUTION STATEMENT

OLIVEIRA JUNIOR, M.V.R; SILVA, R.T.L.; MOREIRA, W.K.O.: designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. SOUZA, J.L.; SARMENTO, C.S.: managed the analyses of the study. RODRIGUES, J.L.S.; SARMENTO, C.S.; OLIVEIRA JUNIOR, M.V.R: managed the literature searches. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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