Determine the Efficiency of Hydraulic Ram-Pumps

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Abstract

From the early nineteenth century, migration from rural to urban areas as an important social phenomenon known throughout the world. Uneconomical construction of water supply systems in sparsely populated rural or impassable rural for drinking, agriculture and animal husbandry, etc. and pull factors in urban, the increase in immigration has been important. Ram pumps are used to transmit water to a higher elevation for more than 200 years. It consists of a system with driver and delivery pipes, delivery and impulse valve and an air chamber. The frequent opening and closure of the valves establish a pulsatile flow which in turn results in pumping water to a higher level. The aim of this research is to develop an equation using experimental data to determine the efficiency of the ram pump. The results are compared with the artificial neural network (ANN) results. According to the results, the proposed equation better than the ANN to estimate the efficiency of the ram pump. Therefore, the presented equation as a simple and the precise equation is recommended to estimate the efficiency. In this equation, the value of RMSE and $R^2$ are 0.0341 and 0.69 respectively.

1. INTRODUCTION

The hydraulic ram is a device (pump) that works without the use of electric energy and fossil fuels and used for pumping water. The hydraulic ram pumping water, using a potential energy of the supply. The hydraulic ram was invented about 200 years ago and used it to date, because it has simple system and inexpensive. Residents of rural to urban migration issue from the early nineteenth century has been the lack of adequate water supply for drinking, agriculture and animal husbandry, expand the use of the hydraulic ram, especially in third world countries. The use of the ram pump is recommended for sparsely populated rural areas and poor third world countries which the construction of water supply systems is costly. The ram pump takes water from the source (the source has head) and pumping to considerable height. The ram pump has two movable valve and an air chamber and pumping water after intermittent cycles. system of the hydraulic ram shown in figure 1.
Figure 1. Components of the hydraulic ram pump

According to the figure 1, the hydraulic ram system consists of several parts: (a) water supply, that can be rivers and springs, (b) drive pipe with definite length and diameter, (c) pump with impulse valve, and (d) delivery valve, (e) air chamber, contains water and air, (f) delivery pipe, (g) storage supply.

The ram pump cycle divided seven to two phases by different researchers. In the three-stage operating cycle of the hydraulic ram for example, there are acceleration, pumping and recoil.

According Young (1995) acceleration of water in the drive pipe occurs when the impulse valve is open and the delivery valve is closed. The impulse valve is open due to spring load or dead weight of valve. At a certain critical velocity, the impulse valve closes due to flow force overcoming the force of spring load or dead weight. Water hammer occurs when the impulse valve closes. Pumping now takes place as shock waves induced by water hammer pass up and down the drive pipe at the speed of sound, the delivery valve opening in response to each pressure pulse. Recoil, the reversal of flow in the drive pipe, occurs at the end of the pumping stage after closure of the delivery valve. The suction resulting from the recoil causes the impulse valve to open and the cycle is ready to begin again. in the hydraulic ram, Optimal conditions occur when the recoil is zero (young (1996a)) thus the operating cycle in optimal conditions consists acceleration and pumping.

2. THE REVIEW OF THE RAM PUMP STUDIES

The ram pump was invented by Whitehurst in 1797. He was made a ram pump manually worked. some time after Whitehurst's invention, two Parisians J.M. Montgolfier and Argant made a ram pump automatically. The invention of the ram pump until the end of the 19th century, There were Theoretical attempts unsuccessfully to explain the performance of the ram pump. Until Zhukovsky first explanation about the ram pumps provided in 1898 (water hammer the main use of the hydraulic ram pump's action Zhukovsky presented) (Filipan et.al. (2003)).

The first rational theoretical analysis of the ram pump behaviour was presented by O’Brien and Gosline (1933). They assumed four time zones in the ram cycle. In the O’Brien and Gosline’s study, Pumping stage occurs when the impulse valve is closed, and after water hammer, propagation of shock waves in the drive pipe.

Lansford and Dugan (1941) assumed six phases in the ram pump cycle. They modified the O’Brien and Gosline’s theory with to performing experiments on 51 and 102 mm ram pumps. Krol (1951) assumed seven phases in ram pump cycle and gave a complex analysis for ram pump. Calvert (1958) studied on drive pipe of ram pump and presented length of drive pipe to diameter of drive pipe ratio (150<L/D<1000).

Iverson (1975) presented an analysis based on Rankine’s equations. In Iverson Analysis, used of the average values of the time-dependent in the One-dimensional unsteady state. Rennie and Bunt investigated Operation of the hydraulic ram pump. They studied various impulse valves and drive pipe diameters experimentally (Young (1997)). Harralson and Cozens (1982) Provided a rationale base for design goals of the ram pump and experiments planned and confirmation previous experiments with using the numerical method of characteristics.

Schiller and Kahangire (1984), with using numerical methods showed the exact theories to predict the performance of ram pumps are complex. They assumed four phases in cycle of ram pump and Regardless of the effect of pressure waves during acceleration due to the complexity. In their model, increase speed or decrease speed during acceleration and duration of the impulse valve closure are linearly. Output model are quantity delivered, pump efficiency and cycle time. They concluded that a general empirical formula is difficult to compare different designs.
Basfeld and Muller (1984), presented a simplified theory is developed from Newton’s equations of motion, taking into account loss factors and boundary conditions. Results from this theory are compared with measurements of plexiglass model of a hydraulic ram, in particular, the time dependence of the flow velocity in the drive pipe, the water volume delivered per work cycle and the efficiency were experimentally determined as functions of various parameters.

Tacke (1988) carried out experiments on 12 commercial ram pumps and explained their behaviour using a modified version of the O’Brien and Gosline theory with the velocity diagram divided into three time zones. Verspuy and Tijsseling (1993), described the operation of ram pump with a simple mathematical model. In their model fluid-structure interaction mechanisms are not included for the sake of simplicity.

Young (1995) presented two simple equations for design ram pump ( \( H = B q h , n L = A q h \) ). These equations containing empirical factors dependent upon ram size, delivery head, material and wall thickness of the drive pipe and the configuration of the impulse valve. Young (1997), presented a simplified analysis for ram pump action and offered four equations for design ram pumps. 

Najm et al. (1999), numerical model for the analysis of water hammer pressure waves in the ram pumps offered and the impact of the waves on the ram pump components were examined.

Maratos (2002) investigated the relationship between quantity delivered and drive pipe diameter and checked the change of velocity in cycle time on the velocity-time diagram. Suarda and Wirawan (2008) examined effect of air chamber on the ram pump performance. They showed that efficiency of the ram pumps without air chamber was about 1 per cent and efficiency of the ram pump with air chamber was about 20 per cent.

### 3. METHODOLOGY

In this study, an equation presented to determine the efficiency of the ram pump using the experimental results of O’Brien and Gosline (1933), Lansford and Dugan (1941) and Krol (1947). O’Brien and Gosline carried out experiments on a 26 mm ram pump of the Gould type. In the O’Brien and Gosline experiments, the length of drive pipe was 15.1 m, supply head was 3.54 m and used three valve strokes with 5.8, 10.9 and 18.5 mm of lengths. The static head to close impulse valve was 0.26m for all of tests. Lansford and Dugan performed three series of tests on each of two Rife ram pumps of diameters 51 mm and 102 mm with different valve loads and strokes. For 51 mm of ram pump, drive pipe length was 16.7 m and supply head was 2.8 m. for the 102mm ram, length of drive pipe and supply head were 16.92m and 2.74 m respectively. The valve loading was not reported, thus it was not possible to determine values of static head to close impulse valve. Krol performed experiments on the 51mm ram pump. Valve strokes ranged from 1.6 mm to 9.5 mm and static head to close impulse valve was varied between 0.066 m and 0.543m. The drive pipe length and the supply head were 18.52 m and 3.96 m respectively.

In the first, proposed an equation for predicting the efficiency of the ram pump using nonlinear regression. Then the results of the proposed equation are evaluated and compared with the Krol experiments data. As well, with development of the hydro-informatics the Artificial Neural Network model has been used. The results of these models are statically compared according to the root mean square error (RMSE), mean percentage error (MPE), standard error of the estimate (SEE), modeling efficiency (EF), correlation coefficient (\( R^2 \)) and The gradient of regression line between results and observations, \( m \), is calculated for evaluating the performance of the equation in a way that the intercept of the equation is zero. It is worth noting that when the \( m \) value is close to one, the predicted results are close to the observations. The error functions are:

\[
MPE = \left( \frac{1}{N} \sum_{i=1}^{N} \left( \frac{P_i - O_i}{O_i} \right) \right) \times 100
\]

\[RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (O_i - P_i)^2} \]

\[
R^2 = 1 - \frac{\sum_{i=1}^{N} (O_i - P_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2}
\]

\[
SEE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (O_i - P_i)^2} \]

\[
EF = \left[ \frac{\sum_{i=1}^{N} (O_i - \bar{O})^2 - \sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} (O_i - \bar{O})^2} \right]
\]

Where \( O \) is the observed parameter, \( \bar{O} \) is the average of observed parameters, \( P \) is the model predicted parameter and \( N \) is the number of data.
According to Young (1997), the effective parameters on the ram pump efficiency are in the equation (6).

\[ f(h, h_m, H, q, Q_c) = 0 \]  \[ \text{[6]} \]

And, the dimensional analysis of variables of the equation 6 yields:

\[ f \left( \frac{h}{h_m}, \frac{qh}{Q_c H} \right) = 0 \]  \[ \text{[7]} \]

Where, \( h \) is delivery head, \( h_m \) is maximum delivery head, \( H \) is supply head, \( q \) is quantity delivered and \( Q_c \) is drive pipe flow rate at impulse valve closure (\( Q_c = \text{velocity to close impulse valve} \times \text{cross-sectional area of the drive pipe} \)). The ranges of experimental data included in the present study are summarized in table 1.

Table 1. The ranges of experimental data used in the present study

<table>
<thead>
<tr>
<th>Researchers Name</th>
<th>Ram Size (mm)</th>
<th>( h/h_m )</th>
<th>Standard Deviation</th>
<th>( qh/Q_c H )</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>O’Brien and Gosline</td>
<td>26</td>
<td>0.505</td>
<td>0.054</td>
<td>0.23</td>
<td>0.138</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.323</td>
<td>0.218</td>
</tr>
<tr>
<td>Lansford and Dugan</td>
<td>51</td>
<td>0.967</td>
<td>0.050</td>
<td>0.479</td>
<td>0.247</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.336</td>
<td>0.031</td>
</tr>
<tr>
<td>Lansford and Dugan</td>
<td>102</td>
<td>0.984</td>
<td>0.067</td>
<td>0.514</td>
<td>0.264</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.445</td>
<td>0.006</td>
</tr>
<tr>
<td>Krol</td>
<td>51</td>
<td>0.597</td>
<td>0.081</td>
<td>0.297</td>
<td>0.132</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.272</td>
<td>0.160</td>
</tr>
</tbody>
</table>

4. RESULTS AND DISCUSSION

Nonlinear regression is a method of finding a nonlinear model of the relationship between the dependent variable and a set of independent variables. Unlike traditional linear regression, which is restricted to estimating linear models, nonlinear regression can estimate models with arbitrary relationship between independent and dependent variables. In this study the statistical analysis was performed using nonlinear regression on the efficiency results using a statistical package for social sciences (SPSS). In the present study, independent and dependent variables are \( h/h_m \) and \( qh/Q_c H \) respectively. The below equation is yielded from nonlinear regression to determine efficiency of the ram pump.

\[ \frac{qh}{Q_c H} = -2.2964 + \frac{2.605}{1 + \exp \left( \frac{h}{h_m} - 1.7045 \right)/0.355} \]  \[ \text{[8]} \]

Figure 2 shows the fit of proposed equation to the experimental data.
In order to compare the result of the proposed equation used of the Artificial Neural Network (ANN) results. ANN is one of the most common network models and generally presented a system of interconnected neurons which can compute values from inputs. A neuron consists of multiple inputs and a single output. There is an input layer that acts as a distribution structure for the data being presented to the networks. This layer is not used for any type of processing. After this layer, one or more processing layers follow called the hidden layers. The final processing layer is called the output layer in a network. This process is repeated until the error rate is minimized or reaches to an acceptable level, or until a specified number of iterations have been accomplished. The ANN models are used to estimate the efficiency of the ram pump. Finally, proposed equation results are compared with the results of the artificial neural network. Figure 3 compares the results of the equation (8) and krol results for $qh/QcH$ and figure 4, compares the results of ANN and krol results for $qh/QcH$. The error functions which are used for evaluating the performance of the equation (8) and results of the artificial neural network are summarized in Table 2.

### Table 2. Statistical error functions of equation 8 and ANN results to krol results

<table>
<thead>
<tr>
<th>Results</th>
<th>Parameter</th>
<th>RMSE</th>
<th>MPE</th>
<th>SEE</th>
<th>EF</th>
<th>$R^2$</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation (8)</td>
<td>$qh/QcH$</td>
<td>0.0341</td>
<td>13.143</td>
<td>0.0042</td>
<td>-1.1995</td>
<td>0.69</td>
<td>1.1192</td>
</tr>
<tr>
<td>ANN</td>
<td>$qh/QcH$</td>
<td>0.0370</td>
<td>13.968</td>
<td>0.0031</td>
<td>-1.5917</td>
<td>0.89</td>
<td>1.1314</td>
</tr>
</tbody>
</table>

Comparing the results of the statistical analysis $qh/QcH$ in table 2 and comparing figures 3 and 4, show that the neural network model performed better than the equation (8) in terms of $R^2$ and EF. In the other terms of table 2, the proposed equation is better than the neural network model. As well, the ANN was developed in compared with experimental results predict the efficiency 13.14% more, while the proposed equation in compared with experimental results estimates the efficiency 11.92% more. Moreover, the proposed equation as a simple, general and precision equation is recommended to estimate the efficiency of the ram pump.

5. **COMPARE THE RESULT**

In present study, proposed an equation to determine the ram pump efficiency. Predict results of the present study equation are compared with ANN predict results and it was concluded that the proposed equation is better than the ANN model. In this section, the result of proposed equation compared with results of computer program based on Lansford and Dugan's theory and experimental measurements of Rife 51mm tests.

In the computer program by changing the dimensionless parameter $h/QcH$, the quantity of pumping water and waste water are calculated and the efficiency determined using $qh/QcH$ equation, Then the efficiency determined with using experimental data (quantity of pumping and waste water).

Finally, the $qh/QcH$ parameter is determined with equation (8) for various experimental $h/QcH$ and the results of computer program and experimental measurements and proposed equation are compared and in figures 5, 6 and 7 are shown.
To determine experimentally efficiency, used of three series tests of Lansford and Dugan on the 51mm ram. In the Lansford and Dugan tests were used three lengths of the valve strokes and loading on the impulse valve. The length of the valve strokes were 8 mm for series 1 and 2 with various loading, and for series 3 the length of the valve stroke was 3 mm. the loading on the impulse valve was not reported.

According to the figures 5, 6 and 7, a large difference are between the experimental measurements and predicted of computer program in the high delivery head. The reason for this difference can be regardless of the less of delivery pipe. The results of the proposed equation are little difference with the experimental measurements and this equation can be used to estimate efficiency of the ram pump.

Figure 5. compare the results of computer program and experimental measurements and proposed equation for serie1, Rife 51mm

Figure 6. compare the results of computer program and experimental measurements and proposed equation for series2, Rife 51mm
6. CONCLUSION
In present study, an equation presented to determine the efficiency of the ram pump using the nonlinear regression of experimental results of O’Brien and Gosline, Lansford and Dugan, and Krol studies. In order to, the results of the present equation was evaluated and compared with the Krol experiments data and the error functions calculated using statistical analysis. On the other hand, predict results of the artificial neural network were compared with the results of krol and the error functions calculated. After compared the error functions of the proposed equation and artificial neural network, it was concluded that, the ANN performed better than the proposed equation in the modeling efficiency (EF) and correlation coefficient ($R^2$). the ANN was developed in compared with experimental results predict the efficiency 13.14% more, while the proposed equation in compared with experimental results estimates the efficiency 11.92% more. With respect to comparing the error functions of proposed equation and ANN, presented equation as a simple, general and precise equation is recommended to estimation the efficiency of the ram pump, as well the proposed equation does not require computer to estimate efficiency of the ram pump. After comparing proposed equation with the artificial neural network, the proposed equation was validated with computer program based on Lansford and Dugan theory and experimental results of Lansford and Dugan tests on the 51mm ram pump. The results of proposed equation compared with results of computer program and experimental measurements. There are large difference between the experimental measurements and predicted of computer program in the high delivery head but the proposed equation has little difference with the experimental measurements and can be used for estimation theory.

7. REFERENCES