Experimental Evaluation of Effective Parameters on Characteristic Curves of Hydraulic Ram-Pumps

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Abstract
The effects of non-dimensional parameters on the characteristic curves of a ram pump were evaluated in this study using an experimental model. To do so, after providing dependent and independent parameters using dimensional analysis, effect of each independent parameter was examined on the dependent parameter. Experimental observations showed that relative pumping discharge (q/Qₚ), relative wasting discharge (Q/Qₚ) and pump efficiency (η) were depended on length to diameter ratio of drive pipe (L/D) and pressure head ratio (h/hₘ). Impulse valve parameter (nD/V₀) was depended on L/D, h/hₘ and Reynolds number of flow in drive pipe. Characteristic curves were presented for ram pump used in this study to estimate dependent parameters as function pressure head ratio for various ratios of length to diameter. In addition, characteristic equations of the used ram pump were introduced using nonlinear regression. Evaluation of results showed that the characteristic curves and equations can be designed a ram pump system with high accurate, and this design method can be proposed for any kinds of ram pumps to use in engineering purpose.

Keywords: Ram pump, dimensional analysis, characteristic curves, non-linear regression, and impulse valve.

1. Introduction
Water supply in remote sites is often chosen with pump driving energy as limiting factors. Some of these factors such as access road and energy sources have been made to limitations in pump choices. On sites that stream with a considerable gradient are available, water can be piped down a grade to power a hydraulic ram pump that will lift water to the higher location in 24 hours a day. A Hydraulic Ram Pump is a device which feasible solution for the geographic and economic condition without an external energy source, such as electricity or fossil fuels. This system can pump water to the rural and tribal areas, where the construction of water transfer systems cannot be justified economically. The ram pump using water hammer energy and the management of its own energy receives from the water supply head, will enable it to pump the water to a considerable height after a periodic operating cycle.
1.1. The working cycle of hydraulic ram pump

The cycle of ram pump is divided into the three phases: acceleration, pumping and recoil. At the start of acceleration phase, the flow in the drive pipe is at rest. Impulse valve is open and the delivery valve is closed. The flow accelerates under the action of the supply head until the dynamic force this flow exerts on the impulse valve is sufficient to cause it to begin closing. Flow velocity in drive pipe continues to increase and the impulse valve starts to close at a certain critical velocity. At the end of acceleration phase the impulse valve is closed rapidly and water hammer phenomenon is occurred. Pumping now takes place as shock waves induced by water hammer passing up and down the drive pipe at the velocity of pressure wave and the delivery valve is opened in response to each pressure pulse and flow is pumped toward the storage tank. Recoil, the reversal of flow in the drive pipe, occurs at the end of the pumping phase after becoming closed the delivery valve. The suction resulting from the recoil causes the impulse valve to open and the cycle is ready to begin again. Components of a ram pump system are shown in figure 1.

Fig1. Layout of hydraulic ram pump system

1.2. Review of previous studies

The ram pump was invented by Whitehurst in 1797 to supply water to a brewery factory. After the invention of the hydraulic ram pump, there were unsuccessful attempts to provide a rational theory to explain the ram pump performance until the early of twentieth century [1]. The first rational theoretical analysis of the ram pump behavior was presented by O’Brien and Gosline [2]. They assumed four time zones in the ram pump cycle. In [2] pumping phase is occurring when the impulse valve is closed, and the propagation of pressure waves occurs in the drive pipe after water hammer. Krol [3] assumed seven phases in the ram pump cycle and gave a complex analysis for it. Rennie and Bunt [4] investigated the operation of the hydraulic ram pump. They studied various impulse valves and drive pipe diameters experimentally. Schiller and Kahangire [5] by using numerical methods concluded that the exact theories for predicting the performance of ram pumps were complex. They assumed four phases in ram pump cycle and ignored the effect of pressure waves during acceleration due to their complexity. In their model, an increase or a decrease in speed during acceleration, and the
duration of impulse valve closure are linearly. The output of their model includes the delivered quantity, pump efficiency and cycle time. They concluded that a general empirical formula couldn’t compare the different designs. Basfeld and Muller [6] presented a simplified theory developing from Newton’s equations of motion and taking into account loss factors and boundary conditions. The results from their theory were compared with the measurements of Plexiglas’ model of a hydraulic ram pump. 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 the functions of various parameters. Tacke [7] carried out some experiments on 12 commercial ram pumps and explained their behavior using a modified version of [2] and the velocity diagram divided into three time zones. Rennie and Bunt [8] presented a graphical approach in order to design ram pumps by using analytical model and experimental validation. Young [9] presented two simple equations to design the ram pump (\( H = BqH, nL = AqH \)). These equations contained some empirical factors which depended upon ram size, delivery head, material, wall thickness of the drive pipe and the configuration of the impulse valve. Young [10] studied Wilcox’s ram pump and presented a simplified analysis under ideal condition (recoil is zero) for ram pump action. Under this condition, equations (1) to (4) offered to design the ram pump. These equations can be used for designing ram pumps in sizes of 19 to 102 mm.

\[
\begin{align*}
  nLD^2 & = 20qH \quad (1) \\
  HD^2 & = 4.6qH \quad (2) \\
  Q_T & = 0.7D^2 \quad (3) \\
  L_{max} & = 110HD \quad (4)
\end{align*}
\]

Young [11] introduced optimum design range for non-dimensional parameters that determined analytically under ideal condition by using experimental results of previous researchers. Najm et al. [12] developed a numerical model for the analysis of water hammer pressure waves in the ram pump and the impact of the waves on the ram pump components was examined. Maratos [13] investigated the relationship between quantities delivered and drive pipe diameter and evaluated the change of velocity in time cycle on the velocity-time diagram. Filipan and Virag [1] presented a mathematical model using method of characteristic. In this model, the mathematical modeling of particular
components such as drive and delivery pipes, supply and storage tanks and set of ram pump explained in detail. Then by using boundary conditions, 11 equations with 11 dependent variables solved by an iterative procedure for each time step of the computational run. The outputs of model presented in the form of pressure and velocity versus time graphs. Suarda and Wirawan [14] examined the effect of air chamber on the ram pump performance. They showed that the efficiency of the ram pump without air chamber was about 1 percent and the efficiency of the ram pump with air chamber was about 20 percent. Saito et al [15] evaluated the effects of the air volume in air chamber on the hydrodynamic characteristics and operating conditions of ram pumps. Evaluations were showed that the peak pressures in the valve and air chambers vary depending on the pump head and the peak pressure in the valve chamber and the peak pressure in the air chamber tend to decrease as the air volume in the air chamber increases. Nwosu and Madueme [16] constructed hydraulic ram pump which is used to increase the head of the falling water. The rate of flow of water, from the tank and pumping water into the tank are designed to operate in an optimum manner. A controlled actuator is used In order to maintain the flow rates. The underground tank is made to store rain water and is capable of meeting the water need of the micro hydropower plant for the off rain periods. Sheikh et al. [17] studied the literature available and prepared a structured design methodology for hydraulic ram pump (HYDRAM) which covers design parameters, design procedure along with the mathematical relationship used for the design work. Yang et al. [18] by using experimental evaluation showed that the adding a short cambered diffuser between the elbow and the impulse valve in the ram pump caused to increase the ram pump efficiency to 53 percent. Inthachot et al. [19] added an off-the-shelf clap check valve on the ram pump and increased the efficiency of pump increased over 30 percent. The results of the field observations showed that this ram pump supplied the irrigation of lands for North area of Thailand with efficiency of 44 percent in range of six week. Mbiu et al. [20] highlighted on design development of a durable and locally made hydram using inexpensive and readily available materials. A test rig was fabricated and used to analyze the different parameters of the hydram. Optimizing these parameters ensures that the hydram performance is enhanced and as a result giving the pump a longer life. Experimental and analytical modelling results were generalized in performance.
charts and compared to commercially available types operating characteristics. These results will enable the targeted users to be able to select appropriate sizes for their water pumping needs.

1.3. Objectives of study

Reviewing in the previous studies about hydraulic ram pumps showed that simultaneous evaluations of all effective parameters on the ram pump performance are not performed. Therefore, the aim of this study is to evaluate the performance of ram pump using the selective effective parameters. To accomplish the objective of this study, several experiments were performed. At first, all effective dimensional parameters on ram pump performance have been identified. Then, numerous experiments have been performed to evaluate the performance of ram pump based on each of the identified effective parameters. The performance results were used to develop characteristic curves that could be used for practical application of ram pump.

2. Materials and Methods

2.1. Experimental set up

Experimental results were used to evaluate effective parameters on ram pump characteristic curves. Thus, by developing an experimental model consists a ram pump set (with 51 mm in diameter) and auxiliary equipment such as pressure control board of delivery head and pressure control board of supply head, the performance of ram pump system was evaluated in research laboratory of Hydraulic and River Engineering of Jundi-Shapur University of Technology. Fig 2 shows a schematic of the experimental model used in this study.

![Fig 2. Schematic of experimental setup]

In order to perform experiments using laboratory model, the flow was connected to the system. Then, by opening the control valve of the supply control board, the supply head was adjusted. By adjusting the control board of delivery head in the desired height, the tests were performed. By the automatic opening and closing of impulse valve, and the occurrence of intermittent cycles, a part of input discharge was pumped and the excess of it was removed from the system through impulse valve as wastewater. Then, the quantities of pumping and wasting discharge and frequency of impulse valve were recorded during of each test. The duration of each test was approved for twenty minutes. In each
scenario, the pump performance was evaluated for delivery heads of 2, 3 and 4 meters versus supply heads of 1 and 1.5 meters. Similarly, the performance of the pump was investigated in delivery heads of 3 and 4 meters versus supply heads of 2 and 2.5 meters. Table 1 shows the governing scenarios in this study.

Table 1. Condition of Length to diameter ratios of drive pipe in this study

2.2. Dimensional analysis

After recording laboratory values, the analysis of the results was carried out. Hence, applying a dimensional analysis and the \( \pi \)-Buckingham theory, the effective parameters on the ram pump performance were determined. According to Fig 1 and hydraulic flow in this category of pumps, the dependent and independent parameters of the pumping system of the ram pump were listed as the following:

The delivery head or pumping head \( (h) \), supply head of water source system \( (H) \), characteristics of drive pipe including pipe modules of elasticity \( (E) \), pipe diameter \( (D) \) and length of pipe \( (L) \), characteristics of fluid including density \( (\rho) \), bulk modules \( (K) \) and dynamic viscosity of fluid \( (\mu) \), acceleration due to gravity \( (g) \), density of the constituent materials of the impulse valve \( (\rho_m) \), friction coefficient of fluid and internal pipe wall \( (f) \), the total input discharge \( (Q_T) \) and maximum pumping head or delivery head \( (h_m) \) indicating the independent parameters of the hydraulic ram pump systems.

On the other hand, the variables such as pumping discharge \( (q) \), wasting discharge \( (Q) \), frequency of impulse valve \( (n) \), the velocity of pressure wave \( (C) \), the critical velocity required to closing impulse valve \( (v_0) \) and pump efficiency \( (\eta) \) indicating the dependent variables. It was assumed that the modulus of elasticity and Bulk modulus only influence on the pressure wave velocity, and the density of the constituent of impulse valve only influence on the critical velocity required to closing impulse valve. On the other hand, the kinematics viscosity of the fluid \( (\nu) \) was used instead of the values of dynamic viscosity \( (\mu) \) and fluid density \( (\rho) \) in order to reduce the independent variables. Thus, the independent variables were limited to the eleven variables including \( (Q_T, h_m, h, H, D, L, f, \nu, g, C, v_0) \), and the dependent variables were limited to \( (q, Q, n, \eta) \). Finally, the dimensional analysis was
conducted based on the dependent and independent variables of the hydraulic ram pump system, and the relationship between independent these parameters was indicated as the following.

\[
\frac{q}{Q_T} = \phi_1\left(\frac{v_0 D}{v}, \sqrt{gh}, \frac{v_0}{C}, \frac{h}{h_m}, \frac{L}{D}, f\right) \quad (5)
\]

\[
\frac{Q}{Q_T} = \phi_2\left(\frac{v_0 D}{v}, \sqrt{gh}, \frac{v_0}{C}, \frac{h}{h_m}, \frac{L}{D}, f\right) \quad (6)
\]

\[
\frac{nD}{v_0} = \phi_3\left(\frac{v_0 D}{v}, \sqrt{gh}, \frac{v_0}{C}, \frac{h}{h_m}, \frac{L}{D}, f\right) \quad (7)
\]

\[
\eta = \phi_4\left(\frac{v_0 D}{v}, \sqrt{gh}, \frac{v_0}{C}, \frac{h}{h_m}, \frac{L}{D}, f\right) \quad (8)
\]

Where, the relative parameter \(v_0 D/v\) indicates Reynolds number, the relative parameter \(\sqrt{gh}/v_0\) indicates Froude number, and the relative parameter \(v_0/C\) indicates the Mach number. On the other hand, \(q/Q_T\) is relative pumping discharge, \(Q/Q_T\) is relative wasting discharge, \(nD/v_0\) is impulse valve parameter, \(\eta\) is pump efficiency, \(h/h_m\) is pressure head ratio, \(L/D\) is length to diameter ratio of drive pipe and \(f\) is friction coefficient.

2.3. Methodology

To present characteristic curves of ram pump, hydraulic features of pumping system such as maximum delivery head and loss values of impulse valve were determined. Losses in the impulse valve can be divided into two parts: (1) loss due to the drag coefficient which was determined using the rule of drag force [3], and (2) loss due to the friction coefficient of impulse valve, measured by water manometer using the slop difference of energy line between the sides of the impulse valve at different lengths of stroke valve. Therefore, attempts were made to provide the empirical equations and graphs to determine the loss coefficients of impulse valve. To measure maximum delivery head of ram pump, after closing control valve that installed on the delivery pipe, and under various laboratory conditions, maximum delivery head with regardless of the loss values in delivery pipe was measured by using pressure gauge. According to the relationship between dependent and independent parameters in equations (5) to (8), and performing experimental evaluation, the effect of independent parameters on the ram pump performance was taken into account. By evaluating the ram pump performance versus the effective parameters on its performance, characteristic curves of ram pump were presented.
Characteristic equations governing on the research were presented to estimate the relative pumping discharge, relative wasting discharge, parameter of impulse valve and pump efficiency. The SPSS software was used in order to detect the nonlinear relationship between the dependent and independent parameters of the dimensional analysis. After the dimensional analysis and the determination of the general form of characteristic equations in this study, it was necessary to change the process of the independent parameters and their effect on the dependent parameters evaluated. To do this, it was necessary to do a statistical analysis. The error functions used in the present study to evaluate the results of the proposed equations include the mean percentage error (MPE), root mean square error (RMSE), correlation coefficient ($R^2$), standard error estimates (SEE) and modeling efficiency (EF).

The gradient of regression line ($m$) between results and experimental observations was calculated for evaluating the performance of the equations in a way that the intercept elevations of them become zero. It is worth noting if the value $m$ is close to one, the predicted results are close to the experimental observations.

3. Results

After recording the experimental observations and evaluating ram pump performance versus Reynolds number, Froude number, Mach number, pressure head ratio, length to diameter ratio of drive pipe and friction coefficient of fluid and pipe, effective parameters were selected. To do so, independent parameters were changed under identical laboratory condition then; the changes of dependent parameters were measured. Experimental observations showed that the changes in Reynolds number had not an effect on the quantities of relative pumping and wasting discharge and pump efficiency. On the other hand, the changes in the Reynolds number had an effect on the impulse valve parameter. On the other hand, the changes in parameters of Froude number, Mach number and friction coefficient had not effects on the ram pump performance and can be neglected. Out of other independent parameters of dimensional analysis, the pressure head ratio and length to diameter ratio of drive pipe are notable. The experimental evaluation of these parameters indicated that the changes ratios of length to diameter of drive pipe and pressure head had significant effects on the ram pump performance. Thus, the effects of these parameters cannot be ignored. Table 2 shows the ranges of experimental observations of dependent and effective independent parameters.
As mentioned in section of material and methods, the loss of impulse valve divided into two parts including the loss caused by friction coefficient and the loss of the drag coefficient. Results of loss values measured for an impulse valve with disc diameter of 35 mm and weight of 135 gr were provided in table 3.

Table 2. The ranges of experimental data used in the present study

Table 3. Experimental values of impulse valve loss in the various valve strokes

In order to facilitate the exploitation of the results presented in table 3, two empirical equations based on the experimental observations were presented in the form of relations (9) and (10) to determine friction coefficient and drag coefficient. Note that these relations are corresponding to the specifications of impulse valve used in this study’s ram pump.

\[ K_d = 0.0453 \times \left( \frac{S_0}{D_v} \right)^{-2.0381}, \quad R^2 = 0.99 \quad \text{RMSE} = 0.08 \]  

(9)

\[ c = 0.7312 \times \left( \frac{S_0}{D_v} \right)^{-1.4141}, \quad R^2 = 0.99 \quad \text{RMSE} = 0.83 \]  

(10)

Out of the other features of the ram pump used in this study, it is necessary to point out to the maximum delivery head. In general, every pump can pump water to a certain height depending on the specifications of the ram pump system. The observations showed that the parameters such as supply head (H) or effect of it on flow velocity in steady state \( \nu = (2gH)^{0.5} \), length to diameter ratio (L/D) and the critical velocity to close impulse valve (\( v_0 \)) have a significant effect on the maximum delivery head. By evaluating the ratio of \( h_m/H \) versus independent parameters of \( \nu/v_0 \) and L/D, a diagram was provided in Fig 3 to determine the maximum delivery head.

Fig 3. Determination head ratio of \( h_m/H \) versus velocity ratio of \( \nu/v_0 \) for different ratios of L/D

Using the statistical functions, an equation was presented to determine the maximum delivery head for the ram pump designed in this study. The mapping between the independent parameters \( L/D \) and \( v/v_0 \) and dependent parameter \( h_m/H \) was presented as the relation (11):
\[
\frac{h_m}{H} = 0.247 \times \left( \frac{L}{D} \right)^{0.729} \times \left( \frac{v}{v_0} \right)^{-0.644}, \quad R^2 = 0.97, \quad RMSE = 0.53
\] (11)

Where \( v_0 \) is the required velocity to close the impulse valve, and \( v \) is flow velocity in a steady state. To determine the critical velocity required for closing the impulse valve, equation (12) was provided based on law of drag force [3].

\[
v_0 = \frac{W_g}{K_d \rho A_v}
\] (12)

Where, \( W \) is weight of impulse valve, \( \rho \) is fluid density and \( A_v \) is disc area of impulse valve.

The aim of this study is presented the characteristic curves of ram pump used in present study. To do so, attempts were made to provide the necessary conditions for estimating the quantities of pumping discharge, wasting discharges, impulse valve parameter and pump efficiency under different conditions. Thus, all experimental observations of the dependent parameters were evaluated in versus the pressure head ratio for different ratios of length to diameter of drive pipe. Figs 4 to 7 show the ram pump characteristic curves to determine the relative pumping discharge, relative wasting discharge, impulse valve parameter and pump efficiency.

**Fig 4.** Characteristic curve to determine the values of \( q/Q_T \) versus \( h/h_m \) for different ratios of \( L/D \)

**Fig 5.** Characteristic curve to determine the values of \( q/Q_T \) versus \( h/h_m \) for different ratios of \( L/D \)

**Fig 6.** Characteristic curve to determine the values of \( nD/v_0 \) versus \( h/h_m \) for different ratios of \( L/D \)

**Fig 7.** Characteristic curve to determine the values of \( \eta \) versus \( h/h_m \) for different ratios of \( L/D \)

In order to facilitate the use of results in Figs (4) to (7), characteristic equations were presented. According to evaluate the effects of independent parameters on the ram pump performance, it was found that relative pumping discharge, relative wasting discharge and pump efficiency were depended...
on changes of length to diameter ratio of drive pipe and pressure head ratio. On the other hand, impulse valve parameter was depended on Reynolds number and ratios of pressure head and length to diameter of drive pipe. The mappings of proposed equations between the dependent and independent parameters were provided as the following:

\[
\frac{q}{Q_t} = \frac{0.15258 \left(\frac{L}{D}\right)^{-0.3971}}{0.04984 \left(\frac{h}{h_m}\right)^{4.2051}}
\]  

(13)

\[
\frac{Q}{Q_t} = 0.56 \left(\frac{L}{D}\right)^{0.1039} \left(\frac{h}{h_m}\right)^{0.2561}
\]  

(14)

\[
\frac{nD}{v_0} = 0.00096 \times \left(\frac{L}{D}\right)^{-0.0679} \times \left(\frac{h}{h_m}\right)^{0.33} \times \text{Re}^{1.087}
\]  

(15)

\[
\eta = -0.2688 + \left(\frac{L}{D}\right)^{-0.0479} - 0.4763 \left(\frac{h}{h_m}\right)^{1.2507}
\]  

(16)

4. Discussion

As mentioned in subsection of methodology, the error functions were used to evaluate the results of study. Statistical analysis is performed on equations (13) to (16) and the brief results of error functions based on the prediction parameters \(q/Q_t\), \(Q/Q_t\), \(nD/v_0\) and \(\eta\) are provided in table 4.

Table 4. The brief results of error functions based on the proposed equations

<table>
<thead>
<tr>
<th>Equation</th>
<th>(q/Q_t)</th>
<th>(Q/Q_t)</th>
<th>(nD/v_0)</th>
<th>(\eta)</th>
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<tbody>
<tr>
<td>(13)</td>
<td>0.0338</td>
<td>2.26</td>
<td>0.0405</td>
<td>0.0105</td>
</tr>
<tr>
<td>(14)</td>
<td>0.0405</td>
<td>0.24</td>
<td>0.0405</td>
<td>0.0105</td>
</tr>
<tr>
<td>(15)</td>
<td>0.0405</td>
<td>0.76</td>
<td>0.0405</td>
<td>0.0105</td>
</tr>
</tbody>
</table>

Statistical analysis of error functions due to the prediction of experimental values by produced equations showed that the equation (13) predicted the relative pumping values by root mean square error of 0.0338. Also, the evaluation of the gradient of regression line between the calculated results and experimental observations showed that this equation predicted relative pumping discharge 2.26 percent less than the experimental observation. On the other hand, the proposed equations had root mean square error of 0.0405 and 0.0105 to estimate the relative wasting discharge and impulse valve parameters, respectively. The evaluation of the gradient of regression line between calculated results and experimental observations showed that the equation (14) predicted the relative wasting discharge 0.24 percent less than the experimental observations. Similarly, the equation (15) predicted the impulse valve parameter 0.76 percent less than the experimental observations. Equation (16) had a
RMSE of 0.0357 to predict the ram pump efficiency. Therefore, this equation predicted it 1.55 percent less than the experimental observations. The other error functions in table 4 showed that the proposed equations, called characteristic equations, can be used to design the ram pump in height accuracy. Figs 8 to 11 show the gradient of regression line based on the predicted values by the proposed equations versus experimental observations, and the correlation coefficient of these equations.

Fig8. The predicted values of $q/Q_T$ by equation (13) versus experimental observations.

Fig9. The predicted values of $Q/Q_T$ by equation (14) versus experimental observations.

Fig10. The predicted values of $nD/v_0$ by equation (15) versus experimental observations.

Fig11. The predicted values of $\eta$ by equation (16) versus experimental observations

In order to design a pumping system using the results in this study, at first length of drive pipe is determined according to the topographical conditions of water supply and installation position of pump device. In addition, diameter of it is selected by taking into account the discharge capacity of supply source and economic conditions. As well, pressure head ratio is estimated after calculating maximum delivery head (eq. 11) and measuring delivery head. In practice, total input discharge ($Q_T$) is depended on capacity of water supply source and it is determined using hydrometric methods or other empirical method. Finally, pumping discharge, wasting discharge, frequency of impulse valve and pump efficiency can be determined using Figs (4) to (7) or equations (13) to (16), respectively. Experimental results showed that, by increasing length of drive pipe, pumping discharge was increased, and wasting discharge and frequency of impulse valve were decreased. On the other hand, increasing length to diameter ratio of drive pipe caused to increase pump efficiency and according Fig
A practical example was presented to explain how to use the proposed method for designing a ram pump system. In this example, source capacity \(Q_T\) of pumping system was 27 l/m, supply head and delivery head were 2.5 and 15 m, respectively. In order to evaluate performance of ram pump used in this study, at first a pumping system includes Wilcox ram pump was designed using Young's method (equations (1) to (4)) that was presented to design Wilcox ram pump. The brief results of system designed were showed in table 5.

In similar condition, ram pump used in present study was designed using proposed method. To evaluate ram pump used in study, attempt was made to consider some features of ram pump system designed in table 5 such as length and diameter of drive pipe. Therefore, independent variables and features of a ram pump used in study were selected and brief of results were showed in table 6. With having sufficient variables and information about pump set and location of it, pumping system of ram pump used in study was designed and steps of design process were presented in table 7.

According to the results in tables 5 to 7, under identical geometric and hydrometric condition the ram pump used in study can be pumped about 3196.8 litres during 24 hours to height of 15 m. However, Wilcox ram pump can be pumped about 2030.4 litres during 24 hours to same height. In addition, comparison performance of ram pump used in study and Wilcox ram pump for various delivery head were showed in table 8. Delivery heads were selected between 6 to 20 m with step of 2 m.

It is worth noting that parameter of efficiency in table 8 was determined using Rankine's efficiency or \(\eta_R = \frac{q(h - H)}{QH}\) that used to compare the performance of ram pumps in identical situation. Brief
results in table 8 show that ram pump designed in present study can be operated with high efficiency and it can pump more discharge in compared to Wilcox' ram in low delivery heads.

5. Conclusions

The results showed that relative pumping discharge \( \frac{q}{Q_T} \), relative wasting discharge \( \frac{Q}{Q_T} \) and ram pump efficiency \( \eta \) are independent from the Reynolds number \( Re \), Froude number \( Fr \), Mach number \( Ma \) and friction coefficient of fluid \( f \). Consequently, dependent parameters are function of pressure head ratio \( \frac{h}{h_m} \) and length to diameter ratio of the drive pipe \( L/D \). However, impulse valve parameter or frequency is function of Reynolds number, pressure head ratio and length to diameter ratio of drive pipe. The characteristic curves and the related governing characteristic equations presented in this study could be used for design and performance evaluation of a ram pump system.

1.5. Acknowledgments

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1.6. References


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Fig5. Characteristic curve to determine the values of $q/Q_T$ versus $h/h_m$ for different ratios of $L/D$
Fig6. Characteristic curve to determine the values of $nD/v_0$ versus $h/h_m$ for different ratios of $L/D$
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Fig8. The predicted values of $q/Q_T$ by equation (13) versus experimental observations
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Fig 2.

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7. delivery valve
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9. pressure gauge
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11. delivery pipe
12. control valve
13. input discharge
14. control valve
15. wasted discharge
16. pumped discharge
Fig 3.

Fig 4.
Fig 5.

Fig 6.
Fig 7.

$$y = 0.9774x$$

Fig 8.

$$y = 0.9774x$$
Fig 9.

Observed Q/QT vs Predicted Q/QT

Best Fit
15% Deviation Line

Fig 10.

Observed nD/v0 vs Predicted nD/v0

Best Fit
15% Deviation Line
$y = 0.9873x$

Fig11.

Tables

Table 1.

<table>
<thead>
<tr>
<th>Number of Scenarios</th>
<th>Length of Drive pipe $L$ (m)</th>
<th>Diameter of Drive pipe $D$ (m)</th>
<th>Length to Diameter ratio $L/D$</th>
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<td>100</td>
</tr>
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<td>0.05</td>
<td>200</td>
</tr>
<tr>
<td>S3</td>
<td>15.30</td>
<td>0.05</td>
<td>300</td>
</tr>
<tr>
<td>S4</td>
<td>10.20</td>
<td>0.02</td>
<td>400</td>
</tr>
<tr>
<td>S5</td>
<td>12.75</td>
<td>0.02</td>
<td>500</td>
</tr>
<tr>
<td>S6</td>
<td>15.30</td>
<td>0.02</td>
<td>600</td>
</tr>
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</table>

Table 2.

<table>
<thead>
<tr>
<th>No.</th>
<th>Dimensionless Parameter</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$q/Q_T$</td>
<td>0.34</td>
<td>0.008</td>
<td>0.16</td>
<td>0.09</td>
</tr>
<tr>
<td>2</td>
<td>$Q/Q_T$</td>
<td>0.99</td>
<td>0.65</td>
<td>0.83</td>
<td>0.09</td>
</tr>
<tr>
<td>3</td>
<td>$nD/\nu_0$</td>
<td>0.27</td>
<td>0.01</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td>4</td>
<td>$L/D$</td>
<td>600</td>
<td>100</td>
<td>364.91</td>
<td>166.35</td>
</tr>
<tr>
<td>5</td>
<td>$h/h_m$</td>
<td>0.86</td>
<td>0.2</td>
<td>0.48</td>
<td>0.18</td>
</tr>
<tr>
<td>6</td>
<td>$v_oD/\nu$</td>
<td>29568</td>
<td>12724</td>
<td>20877</td>
<td>7547</td>
</tr>
</tbody>
</table>

Table 3.

<table>
<thead>
<tr>
<th>Valve Strokes</th>
<th>Velocity of valve closure</th>
<th>Ratio of $S_v/D_v$</th>
<th>Drag Coefficient</th>
<th>Friction Coefficient</th>
</tr>
</thead>
</table>
Table 4.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
<th>RMSE</th>
<th>MPE</th>
<th>SEE</th>
<th>EF</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q/Q_{T}$</td>
<td>(13)</td>
<td>0.03</td>
<td>1.83</td>
<td>0.03</td>
<td>0.91</td>
<td>0.97</td>
</tr>
<tr>
<td>$Q/Q_{T}$</td>
<td>(14)</td>
<td>0.04</td>
<td>0.22</td>
<td>0.03</td>
<td>0.88</td>
<td>0.99</td>
</tr>
<tr>
<td>$nD/v_{0}$</td>
<td>(15)</td>
<td>0.01</td>
<td>1.29</td>
<td>0.01</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td>$\eta$</td>
<td>(16)</td>
<td>0.03</td>
<td>1.83</td>
<td>0.03</td>
<td>0.88</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 5.

<table>
<thead>
<tr>
<th>Step</th>
<th>Parameter design</th>
<th>Equation number</th>
<th>Parameter value</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$D$</td>
<td>Eq. (3)</td>
<td>0.02</td>
<td>m</td>
</tr>
<tr>
<td>2</td>
<td>$L$</td>
<td>Eq. (4)</td>
<td>7.01</td>
<td>m</td>
</tr>
<tr>
<td>3</td>
<td>$q$</td>
<td>Eq. (2)</td>
<td>1.41</td>
<td>Litre/min</td>
</tr>
<tr>
<td>4</td>
<td>$Q$</td>
<td>$Q=Q_{T}-q$</td>
<td>25.59</td>
<td>Litre/min</td>
</tr>
<tr>
<td>5</td>
<td>$n$</td>
<td>Eq. (1)</td>
<td>1.55</td>
<td>min$^{-1}$</td>
</tr>
<tr>
<td>6</td>
<td>Number of cycle per min</td>
<td>-</td>
<td>93</td>
<td>beat/min</td>
</tr>
</tbody>
</table>

Table 6.

<table>
<thead>
<tr>
<th>No.</th>
<th>Independent variables</th>
<th>Symbol</th>
<th>Value</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Total input discharge</td>
<td>$Q_{T}$</td>
<td>27</td>
<td>Liter/min</td>
</tr>
<tr>
<td>2</td>
<td>Length stroke of impulse valve</td>
<td>$S_{0}$</td>
<td>0.01</td>
<td>m</td>
</tr>
<tr>
<td>3</td>
<td>Disc diameter of impulse valve</td>
<td>$D_{v}$</td>
<td>0.03</td>
<td>m</td>
</tr>
<tr>
<td>4</td>
<td>Supply head</td>
<td>$H$</td>
<td>2.5</td>
<td>m</td>
</tr>
<tr>
<td>5</td>
<td>Delivery head</td>
<td>$h$</td>
<td>15</td>
<td>m</td>
</tr>
<tr>
<td>6</td>
<td>Length of drive pipe</td>
<td>$L$</td>
<td>7.01</td>
<td>m</td>
</tr>
<tr>
<td>7</td>
<td>Diameter of drive pipe</td>
<td>$D$</td>
<td>0.02</td>
<td>m</td>
</tr>
<tr>
<td>8</td>
<td>Dead weight of impulse valve</td>
<td>$W$</td>
<td>0.13</td>
<td>Kg</td>
</tr>
<tr>
<td>9</td>
<td>Acceleration due to gravity</td>
<td>$g$</td>
<td>9.81</td>
<td>m/s²</td>
</tr>
<tr>
<td>10</td>
<td>Flow density</td>
<td>$\rho$</td>
<td>981</td>
<td>Kg/m³</td>
</tr>
</tbody>
</table>

Table 7.

<table>
<thead>
<tr>
<th>Step number</th>
<th>Determine dependent variables</th>
<th>Equation number</th>
<th>Parameter value</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Drag Coefficient ($K_d$)</td>
<td>Eq. (9)</td>
<td>0.35</td>
<td>No dimension</td>
</tr>
<tr>
<td>2</td>
<td>Friction coefficient ($c$)</td>
<td>Eq. (10)</td>
<td>3.06</td>
<td>No dimension</td>
</tr>
<tr>
<td>3</td>
<td>Flow velocity in steady state ($v$)</td>
<td>-</td>
<td>4</td>
<td>m/s</td>
</tr>
<tr>
<td>4</td>
<td>Critical velocity ($v_{0}$)</td>
<td>Eq. (12)</td>
<td>1.98</td>
<td>m/s</td>
</tr>
<tr>
<td>5</td>
<td>Maximum delivery head ($h_{ma}$)</td>
<td>Eq. (11)</td>
<td>25.95</td>
<td>m</td>
</tr>
<tr>
<td>6</td>
<td>Rate of pumping discharge ($q$)</td>
<td>Eq. (13)</td>
<td>2.22</td>
<td>Liter/min</td>
</tr>
<tr>
<td>7</td>
<td>Rate of wasting discharge ($Q$)</td>
<td>Eq. (14)</td>
<td>24.14</td>
<td>Liter/min</td>
</tr>
<tr>
<td>8</td>
<td>Frequency of impulse valve ($n$)</td>
<td>Eq. (15)</td>
<td>1.50</td>
<td>Beat/min</td>
</tr>
<tr>
<td>9</td>
<td>Number of cycle per minute</td>
<td>-</td>
<td>90</td>
<td>Beat</td>
</tr>
<tr>
<td>10</td>
<td>Pump efficiency ($\eta$)</td>
<td>Eq. (16)</td>
<td>22.47</td>
<td>%</td>
</tr>
</tbody>
</table>

Table 8.
<table>
<thead>
<tr>
<th>No</th>
<th>$h/H$</th>
<th>$q/Q_T$</th>
<th>$Q/Q_T$</th>
<th>$nD/v_0$</th>
<th>efficiency</th>
<th>$q/Q_T$</th>
<th>$Q/Q_T$</th>
<th>$nD/v_0$</th>
<th>efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.4</td>
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<td>0.869</td>
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<td>0.707</td>
<td>0.014</td>
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</tr>
<tr>
<td>2</td>
<td>3.2</td>
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<td>0.901</td>
<td>0.019</td>
<td>15.83</td>
<td>0.271</td>
<td>0.761</td>
<td>0.016</td>
<td>51.84</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>0.078</td>
<td>0.921</td>
<td>0.019</td>
<td>11.36</td>
<td>0.213</td>
<td>0.805</td>
<td>0.017</td>
<td>35.24</td>
</tr>
<tr>
<td>4</td>
<td>4.8</td>
<td>0.065</td>
<td>0.934</td>
<td>0.019</td>
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<td>0.151</td>
<td>0.844</td>
<td>0.017</td>
<td>22.65</td>
</tr>
<tr>
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<td>0.019</td>
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<td>0.101</td>
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</tr>
<tr>
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<td>0.019</td>
<td>8.69</td>
</tr>
<tr>
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<td>0.956</td>
<td>0.019</td>
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<td>0.044</td>
<td>0.936</td>
<td>0.02</td>
<td>5.47</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>0.039</td>
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<td>0.019</td>
<td>4.67</td>
<td>0.029</td>
<td>0.962</td>
<td>0.021</td>
<td>3.53</td>
</tr>
</tbody>
</table>

Biographies

**Babk Lashkar-Ara** is an Assistant Professor of Civil Engineering at Jundi Shapur University of Technology. He received his PhD from the Shahid Chamran University, Ahwaz, Iran. His research interests include sediment transport, river engineering and hydraulic structures.

**Reza Fatahi-Alkouhi** received the Diploma degree in civil engineering from Shahrekord's conservatory of Fani 1, the Bachelor degree in civil engineering from the Daneshpajoohan institute and higher education and the Master degree in civil and river engineering from Jundi-Shapur University of Technology. Currently, he is Ph.D. student in civil and water resource management from University of Isfahan.