ORIGINAL ARTICLE

Mathematical models for estimating parameters of a pumping system in furrows irrigation

Modelos matemáticos para la estimación de parámetros de un sistema de bombeo en el riego por surcos

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ABSTRACT: The study was carried out at the Tío Pedro farm in the municipality of Venezuela, in the province of Ciego de Ávila, with the objective of proposing mathematical models to estimate the hydraulic parameters of a pumping system using the furrow irrigation technique for the cultivation of black bean. The results showed expected fluctuations in hydraulic parameters such as flow rate, head, hydraulic power, pumping time, and pumped volume. Functional relationships were found between flow and pumping head, as well as between hydraulic power, flow and pumping head. These ratios can improve pump system performance, save energy, and increase pump efficiency. In addition, functions were developed to predict the characteristic curves of the load, the efficiency of the pump and the system in general. These results can improve energy efficiency and water management in agriculture.

Keywords: Pumping Head, Flow, Electrical Power, Hydraulic Power.

RESUMEN: El estudio se realizó en la finca Tío Pedro en el municipio de Venezuela, en la provincia de Ciego de Ávila, tuvo como objetivo proponer modelos matemáticos para estimar los parámetros hidráulicos de un sistema de bombeo utilizando la técnica de riego por surcos para el cultivo del frijol negro. Los resultados mostraron fluctuaciones esperadas en los parámetros hidráulicos como caudal, carga, potencia hidráulica, tiempo de bombeo y volumen bombeado. Se encontraron relaciones funcionales entre el caudal y la carga de bombeo, así como entre la potencia hidráulica, el caudal y la carga de bombeo. Estas relaciones pueden mejorar el funcionamiento del sistema de bombeo, ahorrar energía y aumentar la eficiencia de la bomba. Además, se desarrollaron funciones para predecir las curvas características de la carga, la eficiencia de la bomba y del sistema en general. Estos resultados pueden mejorar la eficiencia energética y la gestión del agua en la agricultura.

Palabras clave: carga de bombeo, caudal, potencia eléctrica, potencia hidráulica.

INTRODUCTION

Since ancient times, water has been an essential element for the survival of humanity. Its management and rational use have allowed the invention of novel pumping machines, in which the human being has used various energy sources to solve energy and environmental problems in agriculture (Ávila-González *et al.*, 2021).

The achievement of higher productions with high and stable yields requires knowledge of the factors that produce greater energy consumption in irrigation, as it is the basis for establishing energy saving strategies in irrigation, taking into account that the increase in irrigation time demand for greater consumption of water and energy (Tornés-Olivera *et al.*, 2016).

In the furrow irrigation system, the input flow, furrow length, irrigation time and infiltration characteristics are variables that affect its performance; however, the efficiency of water application is mainly influenced by the amount of water applied, the infiltration of the soil and the rate of progress (Tornés-Olivera *et al.*, 2016; 2020)

A furrow irrigation system has different components such as the water source, the pumping equipment; as well as the network of channels and ditches for the distribution of water in the irrigation

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plot. Determining the energy efficiency of a pumping system for surface irrigation requires knowledge of the relationship between the electrical power consumed by the pump, the amount of water pumped, the energy consumed by the pump, the operating time of the pump and the hydraulic power supplied by the pump; Therefore, an efficient pumping system with a high energy yield must be capable of supplying a greater amount of hydraulic energy per unit of electrical energy consumed.

The engine power ensures the required transfer of hydraulic power to achieve high pump efficiency with minimal power loss; however, its behavior is influenced by the pumping flow and the discharge pressure according to Amador-Vilariño *et al.* (2020); for this reason, it is essential to understand the relationship between hydraulic power and mechanical power to improve efficiency and reduce operating costs of the system (Pineda-Ortiz & Chica-Arrieta, 2020).

Mathematical models are important tools because they can help improve the energy efficiency of irrigation, simulate the interaction between the different components of an irrigation system, evaluate different irrigation strategies, and make decisions about energy use. They can also favor the design of energy-efficient irrigation systems, which can reduce energy costs and improve the sustainability of agriculture (Perellada-Gamio & Albelo-Martínez, 2020).

Mathematical modeling is a fundamental component for the comprehensive management of water resources and the environment; for this reason, regression techniques are widely used to obtain information through forecasting, but they previously require the measurement and comparison of their performance through different error measurement criteria (Álvarez-Sevilla *et al.*, 2017).

The objective of this study is to propose mathematical models for the estimation of parameters of a pumping system in furrow irrigation that contribute to improving the energy efficiency of irrigation.

MATERIALS AND METHODS

The research was carried out at the Tío Pedro farm in the municipality of Venezuela, Ciego de Ávila province, Cuba, which is located at 21°45'04" North Latitude and 78°46'45" West Longitude.

The experimental area consisted of a completely randomized strip experiment with a length of 251.60 m and a width of 18 m for an area of 4528.8 m^2 (0.45 ha). This surface was subdivided into plots with a length of 62.90 m and a width of 6 m (10 rows) with the purpose of achieving greater control of the experimental variables. Three rows of the central strip were selected as shown in (Figure 1).

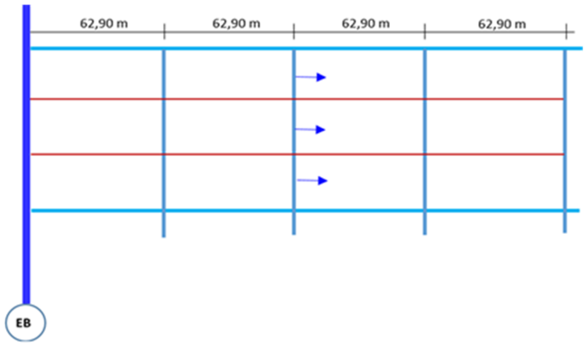

FIGURE 1. Schematic representation of the experimental area.

In the investigation, the cultivation of black beans of the ICA PIJAO variety planted with spacing between plants of 10 cm and between rows of 60 cm was evaluated for a planting frame of 0.24 m^2. The cultivar was planted with an average depth of 20 cm and the norms established for this type of soil were taken into account.

In the study area, an open furrow irrigation system has been established, consisting of a Caprari submerged vertical centrifugal pump type T8C/7/8-71X connected to an asynchronous submerged electric motor with a 100 mm diameter coupling to the hydraulic parts; a hydraulic masonry work for the diversion of water; the main channel dug into the ground and without lining with a superficial width of 1.85 m; base width of 0.12 m; total height of 0.38 m and length of 512 m. This is used to supply water to the internal irrigation network of the farm where the experimental plot is located.

The total workload of the pump was calculated analytically by applying the energy balance between the surface water level in the well and at the outlet of the discharge pipe. In this analysis the reference level is drawn by the base of the pumping equipment. The equations used were:

$$E_a + H_B = E_d + \Sigma h_{Ta-d} \quad (1)$$

$$\left(\frac{P_a}{\rho \cdot g}\right) + \left(Z_a + \frac{v_a^2}{2g}\right) + H_B = \left(\frac{P_d}{\rho \cdot g}\right) + \left(Z_d + \frac{v_d^2}{2g}\right) + \Sigma h_{Ta-d} \quad (2)$$

If the suction and discharge pressures are canceled because they are points where atmospheric pressure acts, the following mathematical expression is obtained to estimate the total workload of the pump:

$$H_B = \frac{v_d^2}{2g} + (Z_d - Z_a) + \Sigma h_{Ta-d} \quad (3)$$

$$v_d = \frac{Q}{A_d} \quad (4)$$

Where E_a is the energy at the selected point in the suction pipe (m); E_d the energy at the selected point in the discharge pipe (m); H_B the total working load of the pump (m); P_a the pressure in the suction pipe (m);

P_d the pressure in the discharge pipe (m); ρ the density of water (kg m^{-3}); g the acceleration of the force of gravity (m s^{-2}); Σh_{Ta-d} total frictional and localized energy losses (m); Z_a the suction height with respect to the base of the pump (m); Z_d the discharge height with respect to the base of the pump (m); v_a the velocity in the suction pipe (m s^{-1}); v_d the velocity in the discharge pipe (m s^{-1}); A_d is the area of the discharge pipe (m^2).

The electrical parameters of the motor measured were the current, the voltage and the power factor with the use of the analyzer of electrical networks of the brand SPERRY DSA-500. The variables were measured in each of the irrigations carried out throughout the period and were repeated five times to obtain the average value.

The main electrical and hydraulic parameters of the motor and the pump evaluated were: hydraulic power, power delivered by the motor, electromechanical performance of the motor-pump assembly, pump performance and electrical power. These calculations were based on the measurement of the rotation speed of the shaft in revolutions per minute (rpm), by means of a digital contact tachometer of the GMKD brand and precision of 0.02%.

The efficiency of the submersible motor was assumed equal to 80%, since modern electric motors have a high efficiency, which can range between 75% and 95%.

$$P_h = \frac{\rho \,.\, g \,.\, Q_B \,.\, H_B}{1000} \quad (5)$$

$$P_e = \frac{\sqrt{3} \,.\, I \,.\, V \,.\, \cos\varphi}{1000} \quad (6)$$

$$P_m = \frac{\sqrt{n_f} \,.\, I \,.\, V \,.\, \cos\varphi}{1000} \quad (7)$$

$$\eta_{em} = \frac{P_h}{P_m} 100 \quad (8)$$

$$\eta_b = \frac{\eta_{em}}{\eta_m} 100 \quad (9)$$

$$P_{en} = \frac{9{,}81 . Q_B \,.\, \Sigma h_{Ta-d}}{\eta_{em}} \quad (10)$$

Where P_h is the hydraulic power (kW); ρ the density of water (kg m^{-3}); g the acceleration due to gravity in (m s^{-2}); Q_B the flow discharged by the pump (m^3 s^{-1}); H_B the total working load of the pump (m); P_e the electrical power (kW); I the measured electric current; V the measured voltage; $cos(\varphi)$ the power factor; P_m motor power or brake power (kW); n_f the number of phases; η_{em} the electromechanical performance of the motor-pump assembly; η_b is the efficiency of the pump (%); η_m engine performance (%); P_{en} the electrical power necessary to compensate losses (kW); Σh_{Ta-d} the total frictional and localized energy losses (m).

RESULTS AND DISCUSSION

Table 1 shows the values of the hydraulic parameters of the pump during the evaluations carried out in the years 2020, 2021 and 2022. It is observed that the fluctuations occurred within the limits indicated in the following intervals: pumping flow, Q_B [60.6 - 63.1 L s^{-1}]; pumping head, H_B [18.0 - 18.7 m]; hydraulic power, P_h [10.7 - 11.5 kW]; pumping time, T_B [2.0 - 3.1 h] and volume pumped, V_B [515.8 - 686.3 m^3].

In (Figure 2) the functional relationship between the variable flow rate and pumping load is presented, which respond to a potential model with a positive exponent; so the trend of the curve is upward. The R^2 determination coefficient is high with a value of 0.9993 and demonstrates the capacity of the model to simulate the load of the equipment at a given moment

TABLE 1. Hydraulic parameters of the pump.

Date	Q_B (Ls^{-1})	H_B (m)	P_h (kW)	T_B (m)	V_B (m^3)
01/07/2020	62.3	18.5	11.3	23	515.8
01/14/2020	62.6	18.6	11.4	2.5	563.4
01/21/2020	62.1	18.4	11.2	2.0	447.1
01/28/2020	62.2	18.5	11.2	2.9	649.4
02/04/2020	60.9	18.1	10.8	2.8	613.9
02/11/2021	61.7	18.3	11.1	3.0	666.4
02/18/2021	61.5	18.3	11.0	3.1	686.3
03/10/2021	62.1	18.4	11.2	2.9	648.3
03/17/2021	60.6	18.0	10.7	2.4	523.6
03/24/2021	62.4	18.5	11.3	23	516.7
03/31/2022	61.9	18.4	11.1	2.6	579.4
04/07/2022	62.5	18.6	11.3	2.5	562.5
04/21/2022	62.2	18.5	11.2	3.0	671.8
04/28/2022	63.1	18.7	11.5	2.4	545.2
Average	62.0	18.4	62.0	2.6	585.0

based on the pumping flow. The mathematical equation that relates these two variables is:

$$H_B = 0{,}43.Q_B^{0{,}91} \quad (11)$$

Where H_B is the pumping head (m); Q_B the pumping flow (Ls^{-1}).

These results coincide with those presented by Brown-Manrique *et al.* (2003) in the analysis of the relationship between the flows and the workload of the pump in a furrow irrigation system with multi-gate pipes, which satisfactorily adjusted to a potential model and allowed its practical use in the improvement of efficiency parameters and uniformity.

In (Figure 3) the functional relationship between hydraulic power and flow is exposed, which respond, as in the previous model, to a positive potential type function with a high coefficient of determination R^2 of 0.9996.

Similar behavior was found in the analysis of the relationship between the hydraulic power and the pumping load (Figure 4), which adjusted favorably to the potential function with a coefficient of determination of 0.9998. The equations that express these previous relationships are:

$$P_h = 0{,}0042.Q_B^{1{,}91} \quad (12)$$

$$P_h = 0{,}023.H_B^{2{,}10} \quad (13)$$

Where P_h is the hydraulic power (kW), Q_B the pumping flow (Ls^{-1}) and H_B the pumping head (m).

These equations can be used to improve the operation of the pumping system, because they allow to predict the value of the hydraulic power based on the flow and the pumping head (m). In this sense, Andrade-Cedeño (2018) reported that hydraulic power affects energy savings and increases the efficiency of the pump, provided that hydraulic losses are reduced. For their part, Santos-Azevedo *et al.* (2016) explained that since hydraulic power is the product of flow and differential pressure (head loss), to save energy it is necessary to achieve high values of this power by controlling both variables.

In (Figure 5) the functional relationship between time and volume is exposed in equipment installed for pumping water in a furrow irrigation system. The relationship found responds to a potential model with a high coefficient of determination of 0.9933 as shown in the following equation:

$$V_B = 227{,}74.T_B^{0{,}98} \quad (14)$$

Where V_B is the volume pumped by the pumping equipment (m^3) and T_B is the pumping time during the irrigation event (s).

Development of functions for the construction of characteristic curves

This paper presents two quadratic functions developed for the purpose of building the

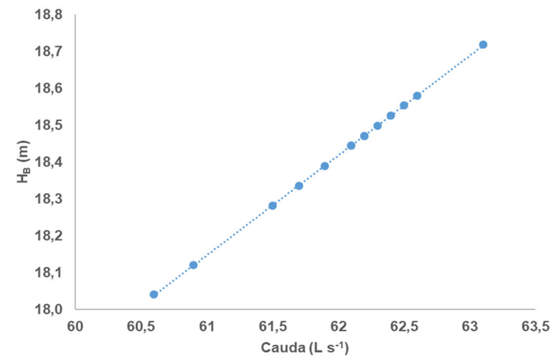

FIGURE 2. Functional relationship between flow and pumping head.

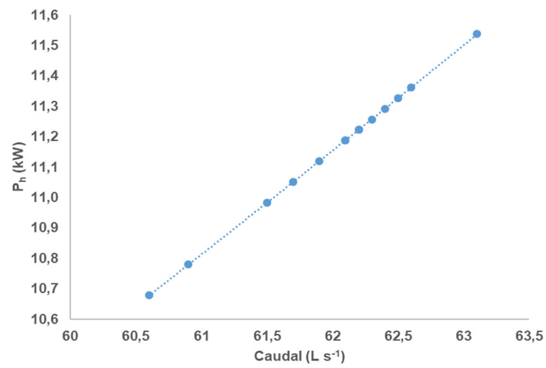

FIGURE 3. Functional relationship between flow and hydraulic power.

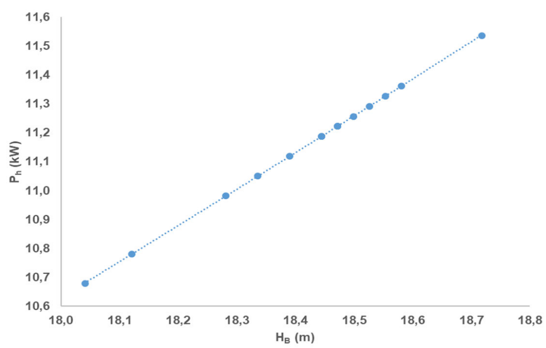

FIGURE 4. Functional relationship between pumping head and hydraulic power.

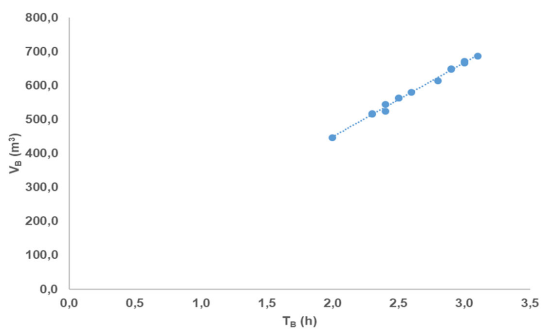

FIGURE 5. Functional relationship between pumping time and volume.

characteristic curves of a centrifugal pump under operating conditions, which were deduced from the considerations presented by Hernández-Ramírez *et al.* (2019) for the mathematical modeling of the coefficient of correction of the pumping head and the criteria of Gavilánez-Luna (2019)) widely used in the estimation of head losses through the Hazen Williams equation.

Based on the above, the problem posed was channeled towards the adaptation of analytical procedures derived from fluid mechanics with the purpose of obtaining the fundamental parameters of a pump that works in the extraction of groundwater for irrigation by gravity, which they vary in relation to the nominal ones offered by the manufacturers; because its determination is carried out under controlled conditions in specialized laboratories. The equations found are:

$$H_B = 18{,}34 - 0{,}0001 Q_B^2 \quad (15)$$

$$\eta = 1.33 Q_B + 0{,}0005 Q_B^2 \quad (16)$$

$$H_{sist} = 11{,}0 + 0{,}00003 Q_B^2 \quad (17)$$

Where H_B is the pumping head (m), Q_B the pumping flow (Ls $^{-1}$), η the pump efficiency (%) and H_{syst} the system head (m).

These equations allow to predict the characteristic curves of the load and efficiency of the pump; as well as the system (Figure 6). Similar works have been developed by different authors such as Martínez Valdés & Riaño-Valle (2018); Martínez Valdés & Riaño_Valle (2019); Valencia-Ochoa *et al.* (2020); Peñaloza & Tolentino-Eslava (2022), who managed to determine the coefficients of the characteristic curves that are the fundamental step for the elaboration of the graphic part.

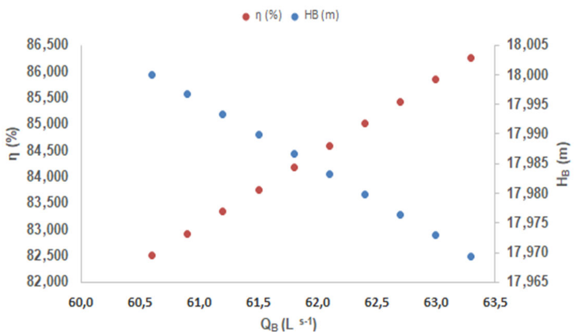

FIGURE 6. Characteristic curve of the pump in operating conditions.

The head-flow curve, the efficiency of the pump for the point of operation of the system, the local losses and the technical state of the pumping unit are the main factors that influence energy consumption and the behavior of energy efficiencies. And hydraulics of a pumping system; for this reason, it is essential to periodically control the technical-economic indicators to achieve their effective and efficient exploitation (Barreda-Trujillo, 2012).

CONCLUSIONS

The results of the evaluations of the hydraulic parameters of a pump that supplies water to a furrow irrigation system showed fluctuations within the expected limits for the variables flow, head, hydraulic power, pumping time and pumped volume. In addition, a functional relationship of the potential type was found between the flow and the pumping head, as well as between the hydraulic power and the flow and the pumping head. These ratios can be used to improve pump system performance and achieve energy savings and increased pump efficiency. Quadratic functions were also developed for the construction of characteristic curves of the pump under operating conditions, which will make it possible to predict the characteristic curves of the load and efficiency of the pump and of the system in general. The periodic control of the technical-economic indicators is essential to achieve an effective and efficient operation of a pumping system.

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