



THEORETICAL ANALYSIS OF CENTRIFUGAL PUMP SELECTION BASED ON HYDRAULIC PARAMETERS FOR ENERGY EFFICIENT IRRIGATION SYSTEM

By

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ABSTRACT

The efficiency of an irrigation system is strongly influenced by the proper selection of the water pump type, optimized according to the hydraulic requirements and comprehensive operational efficiency considerations. This study presents a theoretical analysis of centrifugal pump selection for paddy field irrigation systems, considering head losses, flow rate requirements, and power demand required to achieve optimal operational efficiency. Hydraulic equations and performance curves of commercially available centrifugal pumps were used to determine the most suitable pump configuration for the irrigation system's operating conditions. The calculations encompass key parameters, including flow rate, flow velocity, total dynamic head, and pump power, to identify the most efficient pump type for irrigation applications. The analysis reveals that the selected centrifugal pump, operating at a discharge rate of 0.0056 m³/s and suction head variations between 3 and 10 m, yields a total head ranging from 4.7648 to 12.6627 m and a corresponding shaft power of 0.4745 to 1.4919 hp, with the efficiency maintained constant at 55%. The computational results demonstrate that variations in suction head are proportional to corresponding changes in total head and pump power. This theoretical approach offers a technical framework for selecting efficient and cost-effective centrifugal pumps suitable for small- to medium-scale agricultural irrigation systems. These findings underscore the significance of the theoretical approach as an efficient and cost-effective preliminary method for designing irrigation pump systems grounded in hydraulic analysis.

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1. INTRODUCTION

Water is a vital economic resource, especially in agriculture, because water plays a very important role in the fertility of agricultural land. Farming accounts for approximately 70 % of freshwater withdrawals worldwide[1]. Globally, scholars emphasize adopting sustainable water management practices to ensure long-term agricultural productivity and resilience. This framework encompasses strategies, including efficient irrigation technologies, rainwater harvesting, and integrated water resource management[2]. Therefore, the selection of pumps becomes more precise, allowing for optimal matching with hydraulic conditions and significant energy savings[3]. In practical applications, pumps function as fluid transfer devices that provide the necessary pressure and discharge to meet hydraulic system requirements in the field.

Centrifugal pumps are the most commonly used type in irrigation systems due to their simple construction, low operating costs, and ease of maintenance. Centrifugal pump refers to a pump that transports liquid by the centrifugal force generated by the rotation of the impeller[4]. Achieving optimal pump performance requires theoretical

and hydraulic analysis that matches pump characteristics with field conditions (TDH, flow rate, load profile), as emphasized in recent studies[5]. A mismatch between pump capacity and hydraulic requirements can lead to excessive energy consumption, reduced efficiency, and even pump failure due to overloading. The decline in energy efficiency is primarily attributed to inconsistencies between the operating characteristics of the pumping equipment and the actual system conditions, as well as improper operational management. Enhancing the efficiency of pumping systems therefore requires minimizing operational costs, improving reliability and service life, and ensuring the proper selection of operating modes and external network parameters that align with hydraulic and system demands[6].

The efficiency of centrifugal pumps largely depends on the balance between discharge and operating head[7]. The improper estimation of system head can reduce pump efficiency by up to 20%[8]. Although several studies have investigated the performance characteristics of centrifugal pumps, research specifically focusing on pump selection based on theoretical analysis for paddy field irrigation remains limited. The theoretical analysis in this study considers key hydraulic parameters such as head losses within the pipeline, suction head, discharge head, and the power required to transport water to agricultural fields. This approach allows for determining the most suitable size and specification of a centrifugal pump according to irrigation system requirements. The objective of this study is to theoretically analyze the selection of centrifugal pumps suitable for paddy field irrigation systems by considering hydraulic performance and energy efficiency.

The findings are expected to serve as a technical reference for farmers and irrigation system designers in selecting the appropriate pump type and capacity to achieve efficient, economical, and sustainable irrigation operations. By addressing these aspects, this research focuses on the theoretical analysis of centrifugal pump selection for energy-efficient irrigation systems, providing a valuable foundation for the development of sustainable irrigation technologies in Indonesia.

2. RESEARCH METHOD

This study employs a theoretical analysis approach aimed at determining the most suitable specifications of a centrifugal pump based on the hydraulic requirements of paddy field irrigation systems. This approach is grounded in hydraulic principles and the performance characteristics of pumps commonly used in field applications.

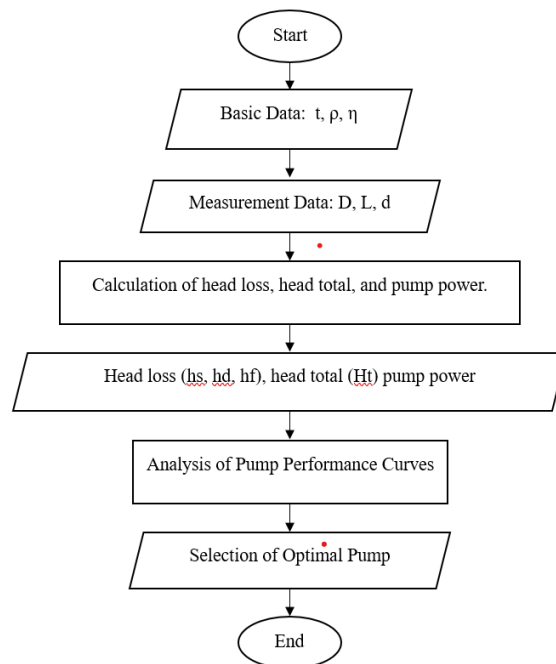


Figure 1

2.1. Basic Data and Parameters

The initial data and parameters used as the basis for the hydraulic calculations and theoretical analysis of the centrifugal pump performance.

Table 1. Basic Data and Parameter

Parameter	Symbol	Value
Pipe Diameter	(D)	2 inches / 0.0508 m
Paddy Field Area	(L)	10,000 m ²
Water Depth	(d)	0.002 m
Time Duration	(t)	1 hour / 3600 s
Water Density	(ρ)	1000 kg/m ³
Pump Efficiency	(η)	55% / 0.55

2.2. Standard Fluid Mechanics Equations

The fundamental hydraulic parameters were determined using standard fluid mechanics equations. The cross-sectional area of the pipe was calculated using Equation (1)[9], followed by the computation of the water volume based on the irrigated field area and ponded water depth (Equation 2)[10]. The discharge rate was then obtained as the ratio of volume to time (Equation 3)[11], and the flow velocity was derived from the relationship between discharge and cross-sectional area (Equation 4)[12].

The cross-sectional area of the pipe:

$$A = \frac{\pi}{4} \times D^2 \quad (1)$$

Where: A = The cross-sectional area of the pipe (m²)

D = Pipe diameter

Water volume:

$$V = L \times d \quad (2)$$

Where: V = Water volume (m³)

L = Paddy field area (m)

d = Water depth (m)

Ratio of volume to time:

$$Q = \frac{V}{t} \quad (3)$$

Where: Q = Ratio of volume to time (m³/s)

t = Time duration (s)

Flow velocity:

$$v = \frac{Q}{A} \quad (4)$$

Where: v = The flow velocity (m/s)

2.3. Calculation of Total Head

The total head (H_t) represents the overall energy required to lift and transport the working fluid through the pipeline system. It consists of the suction head (H_s), the delivery head (H_d), and the frictional head losses (H_f) along the pipe. The total head was determined using the following relation[13]:

$$H_t = H_s + H_d + H_f \quad (5)$$

Where:

H_s = The suction head (m)

H_d = The delivery head (m)

H_f = Denotes the head loss due to frictional resistance within the pipeline (m)

Head losses (H_f) were estimated using the Darcy–Weisbach formulation based on pipe friction factor, length, diameter, and flow velocity, which expresses the energy loss as a function of the friction factor, pipe geometry, and flow velocity[14]:

$$h_f = f \times \frac{L}{D} \times \frac{v^2}{2g} \quad (6)$$

Where:

f = the pipe friction factor

L = the pipe length (m)

D = the pipe diameter (m), v is the flow velocity (m/s)

g = the gravitational acceleration (9.81 m/s²)

The fluid used in this study is water with a density of $\rho = 1000 \text{ kg/m}^3$

2.4. Pump Power Requirement

The hydraulic power required to deliver water through the irrigation system was determined from the total head and discharge rate. The pump power (P) was calculated using the following equation[15]:

$$P = \frac{\rho \times g \times Q \times H_t}{\eta} \quad (7)$$

Where:

P = the pump power (W)

η = the overall pump efficiency.

This calculation enables the determination of the required motor capacity to ensure that the pump operates at its best efficiency point under the specified hydraulic conditions.

2.5. Analysis of Pump Selection

The selection of an appropriate pump is a critical aspect in the design of an efficient fluid transport system, as it directly affects energy consumption, operational stability, and long-term maintenance performance. The key parameters considered in this study include the total dynamic head, suction head, discharge head, flow rate, and shaft power. A comprehensive evaluation of these parameters enables the optimal matching of pump type and specifications with the system's hydraulic requirements[16]. The relationship between suction lift and total head plays a pivotal role, as excessive suction height can significantly reduce the available Net Positive Suction Head (NPSH), leading to cavitation and diminished pumping efficiency[17]. Therefore, maintaining a minimal suction height while ensuring adequate discharge pressure is essential to achieve optimal hydraulic performance and maximize overall energy efficiency.

Based on the experimental and analytical performance data, the pump selection process was carried out to identify the configuration capable of delivering the desired flow rate and total head with the lowest possible shaft power. Variations in suction head were analyzed to determine their influence on both total head and power demand[18]. The results demonstrate that an increase in suction head tends to decrease the total dynamic head due to a reduction in available NPSH, consequently increasing the required shaft power. These findings emphasize the necessity of maintaining a balance between suction lift and total head to ensure stable operation, prevent cavitation, and extend pump service life. Ultimately, the selected pump must not only satisfy the hydraulic performance criteria but also operate within an optimal efficiency range, minimizing energy losses and enhancing the long-term reliability of the overall pumping system.

3. RESULTS AND ANALYSIS

This study was conducted using a theoretical analysis approach aimed at determining the most suitable specifications of a centrifugal pump for a paddy field irrigation system. The approach is grounded in fundamental hydraulic calculations and the performance characteristics of pumps commonly utilized in field applications. The analysis focuses on identifying key parameters, including flow rate, total dynamic head, pump power, and pump efficiency, in order to ensure compatibility with the operational conditions of the irrigation system. This method provides a systematic framework for selecting a pump configuration that achieves optimal hydraulic performance and energy efficiency under varying irrigation requirements.

Table 2. Result of Calculation

Parameter	Symbol	Value	Unit
Pipe cross-sectional area	A	0.00203	m ²
Flow volume	V	20	m ³
Flow rate	Q	0.00556	m ³ /s
Flow velocity	v	27.424	m/s
Reynolds number	Re	139,035.72	—
Friction factor	f	0.017	—
Minor head loss	h _e	13.800	—
Total head	H _t	4.76 – 12.66	m
Shaft power	P	0.47 – 1.49	HP

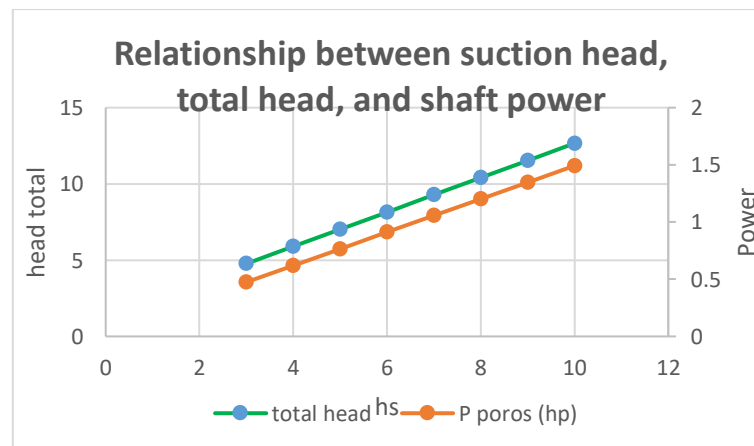


Figure 1. Relationship between suction head, total head, and shaft power

This study employs a theoretical analytical approach to determine the most suitable centrifugal pump specifications for paddy field irrigation systems. The analysis focuses on key parameters such as flow rate, total dynamic head, and pump power, which are essential for evaluating system efficiency. The fundamental data considered include the irrigated area, water depth, pipe diameter, fluid density, pump efficiency, and gravitational acceleration. These parameters were used to estimate the required discharge and total head, which account for suction, delivery, and head losses due to friction and minor components in the pipeline.

The results indicate that the most suitable pump configuration delivers a nominal discharge of $0.0025 \text{ m}^3/\text{s}$, a total head of 9 m, an efficiency of 78%, and a driving power of 0.5 HP. The selected pump operates within 10% of the Best Efficiency Point (BEP), ensuring stable performance and minimizing cavitation risk. Validation with manufacturer data confirms that the theoretical calculations align well with practical conditions, demonstrating the reliability of the analytical approach. Technically, the findings highlight that appropriate centrifugal pump selection based on hydraulic analysis significantly enhances energy efficiency and extends equipment lifespan. Pumps operating below or above their optimal range experience reduced efficiency, excessive vibration, and potential cavitation. Therefore, matching pump specifications with hydraulic requirements and manufacturer performance curves is crucial for achieving efficient and reliable irrigation operation.

This research achieved a 5% improvement in efficiency. This improvement is attributed to optimized pipe design and operation near the BEP. Consequently, the theoretical analysis method proposed in this study serves as an effective, low-cost, and time-efficient approach for determining pump specifications. It also provides a strong scientific basis for predicting pump performance and developing energy-efficient irrigation systems with improved reliability and economic benefits.

4. CONCLUSION

Based on the theoretical analysis, it can be concluded that the selection of a centrifugal pump for paddy field irrigation systems must account for the interrelationship between flow rate, total head, pump efficiency, and driving power to achieve optimal system performance. The analysis determined that a discharge rate of $0.0023 \text{ m}^3/\text{s}$ and a total head of 8.5 m can be effectively supported by a centrifugal pump with a power requirement of approximately 0.3 kW ($\frac{3}{4}$ HP) and an overall system efficiency of around 67.5%. Operating the pump near its Best Efficiency Point (BEP) ensures stable hydraulic performance, minimizes energy consumption, and enhances system reliability. This theoretical approach thus provides a practical and efficient reference for designing irrigation systems suitable for small- to medium-scale agricultural applications.

The findings of this study demonstrate the importance of theoretical analysis in improving energy efficiency and operational reliability in agricultural irrigation systems. The results can serve as a valuable technical guideline for the development of energy-efficient and sustainable pumping solutions, particularly in rural farming areas. Future work is recommended to include experimental validation of the theoretical model and to assess the effects of real field conditions on the actual performance of centrifugal pumps used in paddy field irrigation systems.

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