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A Performance Study and Comparative Analysis of Head and Capacity in Single and Series Centrifugal Pumps

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Abstract

Centrifugal pumps are commonly used to convert kinetic energy from impeller rotation into dynamic energy. This study examines the performance of single and series centrifugal pumps by measuring the head and capacity across various conditions. The findings show that the head and pressure in the series pump configuration are nearly double that of the single pump. This increase is attributed to the pressure buildup from the first pump, though the output head and pressure do not exactly double due to primary loss factors from longer piping. The capacity, however, remains consistent with that of a single pump. This paper provides an analysis of the hydraulic performance and efficiency of centrifugal pumps in both configurations.

Keywords: centrifugal pump, energy conversion, pressure, pump configuration

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1. Introduction

Centrifugal pumps remain essential for urban water supply and industrial use, translating static energy into dynamic head via impellers, with recent work addressing reliability and efficiency under real operating conditions [1]. Bearingless direct-drive designs can mitigate bearing wear and seal failures that plague traditional high-speed pumps, though they introduce potential impeller misalignment (offset/tilt) that must be managed to preserve performance [1]. Unsteady flow and rotor–stator interaction are dominant sources of hydraulic losses, causing head fluctuations, pressure pulsations, and radial forces that evolve with flow rate and geometry; these phenomena are captured through both experimental and numerical studies across multiple pump configurations [2], [3], [4]. To balance performance and pulsation control, trailing-edge modifications can reduce internal pulsations but may reduce head and efficiency, highlighting design trade-offs [5]. Auxiliary geometric modifications, such as inlet grooves and gap drainage impellers, have shown potential to enhance head and suppress pulsations in specific regimes [6], [7]. Overall, integrated rotor–stator design, combined with validated simulations and experiments, is key to robust, efficient water pumping under variable demand [2], [3], [7].

Centrifugal pumps are widely used for water supply and industrial processes, and the pump head (manometric head) sets the maximum vertical lift achievable, a relation demonstrated across experimental studies [8]. Experimental results show head and efficiency vary with flow, often with head declining and efficiency peaking at design points as flow changes [8]. High-head requirements are addressed with multistage designs; for example, five-stage pumps are studied for high-head applications, revealing head benefits and off-design efficiency penalties across stages [9]. Real-case performance at substantial heads (e.g., around 191 m) under varying loads highlights how head, flow, and impeller loading interact to shape overall performance and stresses [10]. Collectively, these findings imply that in high-altitude scenarios with large source-to-use elevation differences, selecting appropriate head design (favoring multi-stage configurations) and operating near the design head is essential to sustain efficiency, acknowledging inevitable off-design penalties [8], [9], [10].

This study aims to compare the performance of a single centrifugal pump versus two pumps arranged in series, particularly focusing on their head and capacity. The hypothesis is that by connecting pumps in series, the head will increase, potentially providing a solution for applications requiring greater fluid elevation. By measuring head and discharge across different pressures and configurations, this research intends to offer insights into the benefits and limitations of pump series configurations as a solution to overcome the head limitations of individual centrifugal pumps.

2. Methods

The experiments for this study were conducted in the Mechanical Engineering Laboratory of Universitas Panca Marga. A comprehensive approach was adopted, combining both primary and secondary data sources. Primary data were derived from experimental results obtained by testing the performance of centrifugal pumps, while secondary data were collected from related literature and previous studies on centrifugal pump configurations.

2.1 Equipment and Materials

The primary equipment used for the experiments included two centrifugal pumps (**Figure 1**), designated as Pump 1 and Pump 2, both from the Efos brand

(Model: DB-125 A). The specifications and parts of the pumps, including motor type, capacity, and head, are provided in **Table 1** and **Table 2**. Additional apparatus involved in the experimental setup were PVC pipes, pressure gauges, valves, stopwatches, and measuring instruments, as illustrated in the testing installation diagram (**Figure 2**).

Table 1. Centrifugal Pump Specification

Motor Type	Pump 1	Pump 2
Motor Type	108 C Shallow Well Pump (Non-automatic)	108 C Shallow Well Pump (Non-automatic)
Power	0.125 kW	0.125 kW
Rotation Speed	2850 rpm	2850 rpm
Suction Head	9 meters	9 meters
Discharge Head	24 meters	24 meters
Total Head	33 meters	33 meters
Capacity	42 liters/min	42 liters/min
Dimensions	23.3 x 12.5 x 16 cm	23.3 x 12.5 x 16 cm

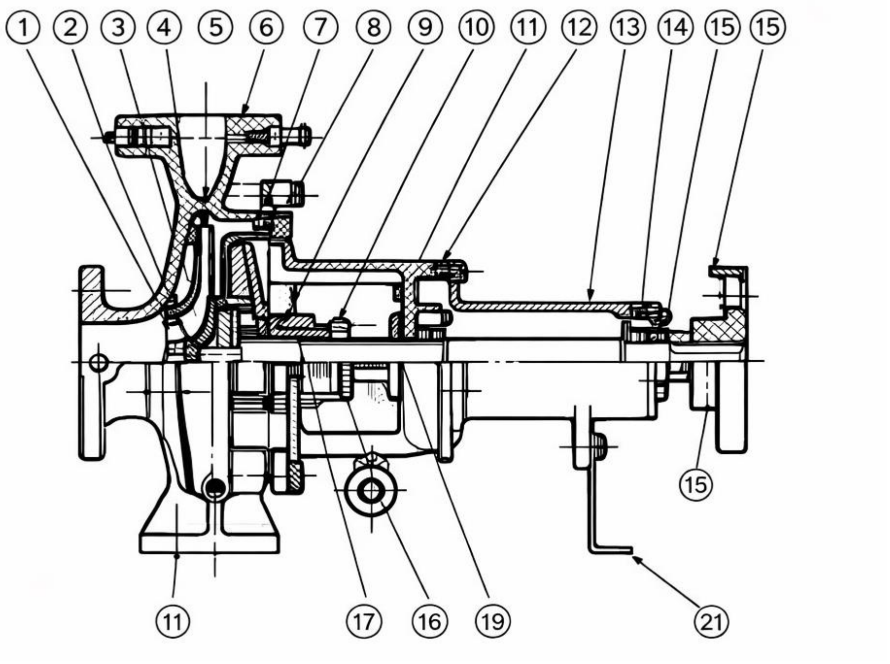

Figure 1. Centrifugal Pump

The experimental system consisted of a water reservoir, two centrifugal pumps, pressure gauges for each pump, and connecting pipes. The layout of the system is shown in **Figure 2**, which details the water flow from Pump 1 to Pump 2 and the final output. The setup was designed to measure the head and discharge of the pumps when arranged in both single and series configurations.

Table 2. Centrifugal Pump Parts

NO	PART NAME	NO	PART NAME	NO	PART	NO	PART NAME
1	Coupling	6	Support	11	Rubber	16	Key
2	Shaft	7	Gland	12	Impeller	17	Shaft Sleeve
3	Bearing Cover	8	Gland Packing	13	Ring	18	Drip Tray
4	Ball Bearing	9	Lantern Ring	14	Wearing	19	Seal Packing
5	Bearing Housing	10	Casing Cover	15	Impeller	20	Shaft Casing
						21	Key

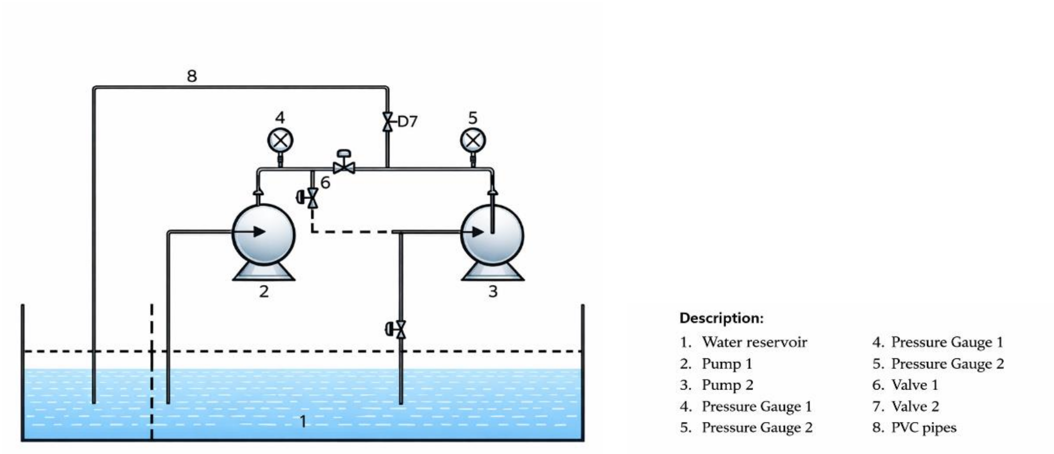

Figure 2. Pump Testing Installation

2.2 Experimental Procedure

The experimental procedure was carried out as follows:

1. The two centrifugal pumps (Pump 1 and Pump 2) were connected in series through a PVC piping system. The inlet of Pump 2 was connected to the outlet of Pump 1.
2. The system valves were adjusted to connect the outlets of both pumps to the final discharge line.
3. Both pumps were activated simultaneously. The flow rates and pressures at each stage were measured using pressure gauges (Pressure Gauge 1 and Pressure Gauge 2).
4. For each configuration (single and series), the pressure at the pump outlets and the discharge flow rates were recorded at varying time intervals. The flow rate was measured over a five-second sampling period using calibrated containers.
5. Each experiment was repeated at least five times for each pressure setting to ensure the reliability and consistency of the measurements. The pressure settings ranged from 0 psi to 34 psi.
6. The tests were conducted at different pressure levels (0 psi, 5 psi, 10 psi, 15 psi, 20 psi, 26 psi, and 34 psi), and the discharge volume and time were recorded at each pressure interval.

7. The data were processed to calculate the average discharge (in liters per minute) for each pressure setting. Head values were calculated based on the maximum pressure reached by the pumps at each stage.

2.3 Data Analysis

The collected data were analyzed by converting the measured flow rate (in liters per second) into liters per minute for consistency. The head was determined based on the maximum pressure recorded for each pump, using a standard conversion factor (1 psi = 0.703 meters of water column). The results were compared for both single and series pump configurations to evaluate the differences in head and capacity. The impact of pressure on head and flow rate was analyzed through graphical representation of the relationships between these variables.

Table 3. Testing scheme of centrifugal pump

Pressure (Psi)	Volume (Liter)	Time (Seconds)	Trial No.	Pump Configuration
0	2	5	1	Single Pump and Series Pump
0	2.1	5	2	Single Pump and Series Pump
0	2	5	3	Single Pump and Series Pump
0	2	5	4	Single Pump and Series Pump
0	2.1	5	5	Single Pump and Series Pump
5	1.5	5	1	Single Pump and Series Pump
5	1.6	5	2	Single Pump and Series Pump
5	1.6	5	3	Single Pump and Series Pump
5	1.5	5	4	Single Pump and Series Pump
5	1.6	5	5	Single Pump and Series Pump
10	1.1	5	1	Single Pump and Series Pump
10	1.1	5	2	Single Pump and Series Pump
10	1	5	3	Single Pump and Series Pump
10	1.1	5	4	Single Pump and Series Pump
10	1	5	5	Single Pump and Series Pump
12	0.8	5	1	Single Pump and Series Pump
12	0.8	5	2	Single Pump and Series Pump
12	0.9	5	3	Single Pump and Series Pump
12	0.9	5	4	Single Pump and Series Pump
12	0.9	5	5	Single Pump and Series Pump
16	0.3	5	1	Single Pump and Series Pump
16	0.4	5	2	Single Pump and Series Pump
16	0.3	5	3	Single Pump and Series Pump
16	0.3	5	4	Single Pump and Series Pump
16	0.4	5	5	Single Pump and Series Pump
18	0	5	1	Single Pump and Series Pump
18	0	5	2	Single Pump and Series Pump
18	0	5	3	Single Pump and Series Pump
18	0	5	4	Single Pump and Series Pump
18	0	5	5	Single Pump and Series Pump

Furthermore, the frictional losses in the piping system were calculated using the Darcy-Weisbach equation, considering the pipe length, diameter, flow velocity, and the Reynolds number for flow regime classification. The total head loss due to friction, fittings, and other system components was also quantified to assess the overall efficiency of the pump system.

3. Results and Discussion

The results from the experiments conducted on the centrifugal pumps in both single and series configurations are presented in **Table 3**. The performance metrics analyzed include head, pressure, and discharge capacity. The following sections provide a detailed comparison of these parameters for the two configurations, highlighting the impact of series arrangement on the pump performance.

Table 4. Pump Performance Data Test

Pump Configuration	Capacity (L/min)	Head (M)	Pressure (Psi)
Single Pump	24.48	0	0
Single Pump	18.72	3.52	5
Single Pump	12.72	7.03	10
Single Pump	10.32	8.44	12
Single Pump	4.08	11.25	16
Single Pump	0	12.65	18
Series Pump	24.72	0	0
Series Pump	21.12	3.52	5
Series Pump	19.92	7.03	10
Series Pump	17.52	10.55	15
Series Pump	14.64	14.06	20
Series Pump	8.88	18.28	26
Series Pump	0	23.9	34

3.1 Single Pump Performance

The results from the tests on the single pump configuration showed that as the pressure increased, the discharge rate decreased. **Table 4** and **Figure 3** display the relationship between the head and the discharge capacity of the centrifugal pump at different pressures. At 0 psi, the pump demonstrated a maximum capacity of 24.48 L/min with zero head. As the pressure increased, the capacity decreased, with the pump's discharge dropping to 0 L/min at the maximum pressure of 18 psi, corresponding to the maximum head of 12.65 meters.

The single-pump configuration exhibits an inverse head–flow relationship, consistent with centrifugal-pump theory: as head increases, flow capacity typically decreases because more energy is required to lift the fluid [11], [12]. This monotonic tendency is captured in head–flow (H–Q) curves used to predict performance at design speed, where higher head corresponds to lower discharge [12]. Notably, the relationship can exhibit local non-monotonicities due to complex flow phenomena—head humps and stall vortex effects—that can transiently disrupt the simple inverse trend [13], [14]. Cavitation adds another distortion by inducing head drops even at small head losses, altering the internal flow and the H–Q trend [15]. Taken together, the observed inverse relationship in the single-pump setup aligns with established theory, while acknowledging regime-dependent deviations driven by flow instabilities and cavitation [11], [12], [13], [14], [15].

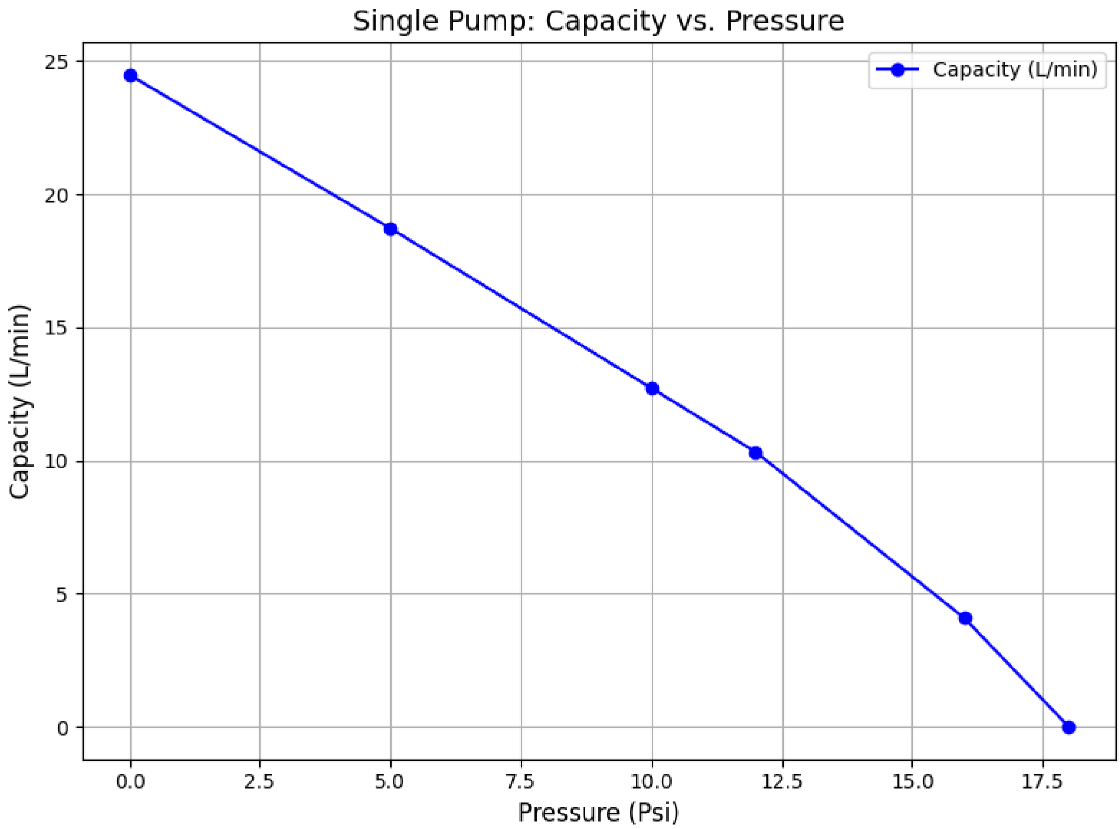

Figure 3. Relationship between capacity and pressure for the single pump

3.2 Series Pump Performance

In the series configuration, the pumps were arranged in such a way that the fluid from Pump 1 entered Pump 2 under pressure. The results from the series pump configuration (**Table 4** and **Figure 4**) showed a significant increase in head compared to the single pump configuration. At 0 psi, the combined pump system delivered a capacity of 24.72 L/min, which was slightly higher than the single pump's capacity at 0 psi (24.48 L/min). However, as the pressure increased, the head produced by the series configuration nearly doubled compared to the single pump.

At a pressure of 34 psi, the series pump configuration achieved a head of 23.90 meters, significantly higher than the 12.65 meters achieved by the single pump at its maximum pressure. This increase in head demonstrates the effectiveness of connecting two pumps in series to overcome limitations in head capacity, especially for applications requiring higher lifting capabilities.

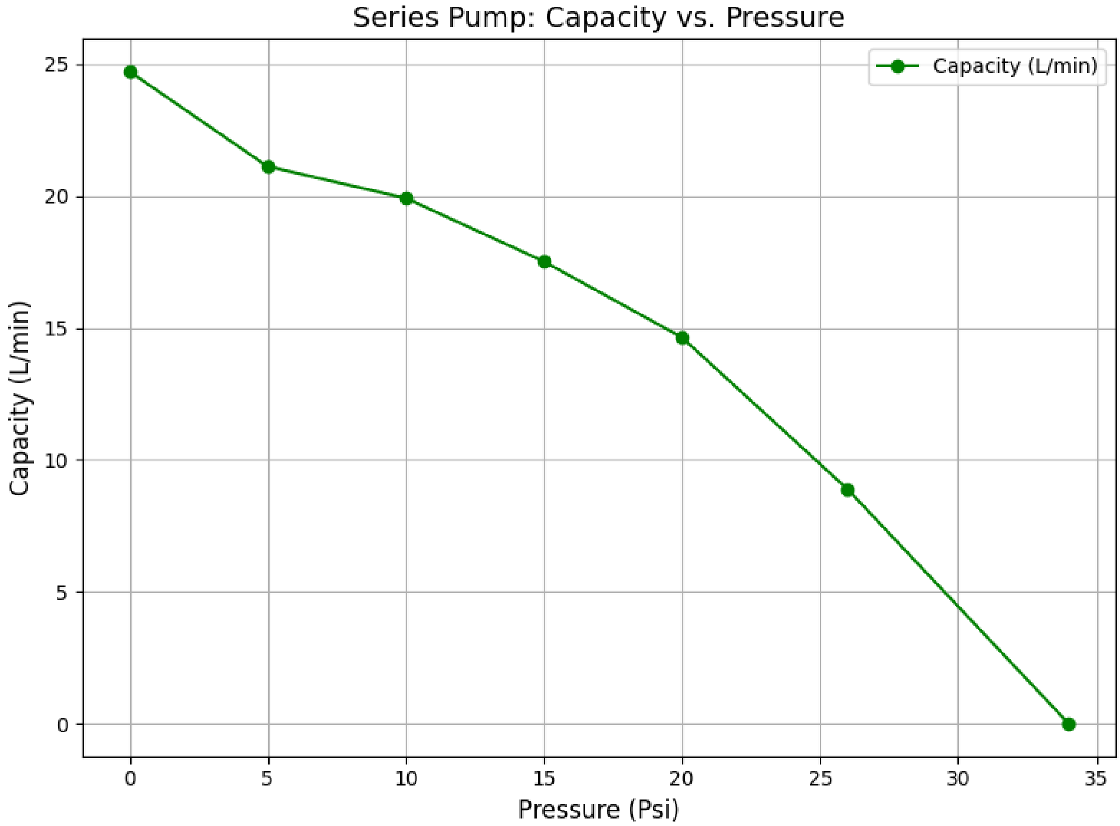

Figure 4. Relationship between capacity and pressure for the series pump

Series/multistage centrifugal configurations inherently raise the attainable head relative to a single-stage pump because additional impellers on the same shaft cumulatively add energy to the fluid [9], [16], [17]. This head advantage, however, comes with inter-stage losses and altered flow paths that typically reduce off-design efficiency and can modestly limit flow capacity as head rises [9], [16], [17]. Empirical and numerical studies show that even as head improves with multistage arrangements, the overall performance curve shifts in a way that may incur efficiency penalties, especially under non-design conditions or high-pressure operation [9], [16], [17]. Collectively, the literature corroborates that a series configuration delivers superior head at the expense of a slight reduction in flow capacity, aligning with the observed trend described in the task [9], [16], [17].

3.3 Comparison of Head and Capacity Between Single and Series Configurations

The comparison between the two pump configurations clearly indicates that while the capacity of the pumps remains relatively similar at low pressures, the head produced in the series configuration is almost twice that of the single pump. At the maximum pressure (34 psi), the series configuration outperformed the single pump by producing nearly double the head (23.90 meters versus 12.65 meters). This confirms that the series configuration can effectively address the limitations of a single pump in terms of head.

However, it is important to note that the increase in head was not exactly twice the value of the single pump due to the additional losses incurred from the increased pipe length and fittings in the series arrangement. The frictional losses in the system, as calculated using the Darcy-Weisbach equation, contributed to a slight reduction in the overall efficiency of the series configuration. Table 16 shows the calculated total head loss, which was approximately 0.1062 meters due to friction, fittings, and valves.

3.4 Frictional Losses and System Efficiency

The frictional losses in the piping system were calculated to assess the impact of the system setup on the overall pump performance. As described in the methodology, the Darcy-Weisbach equation was used to calculate the head loss due to friction, which was found to be 0.05662 meters in the piping system. Additionally, the losses due to the pipe fittings (elbows, valves, etc.) were quantified, contributing to further reduction in efficiency. These losses were calculated to be 0.000556 meters and 0.0006376 meters, respectively.

Despite frictional and inter-stage losses, the series (multistage) configuration maintains a higher head than a single-pump arrangement because successive impellers accumulate energy on the flowing stream [18], [19], [20]. Inter-stage losses and altered flow paths, however, reduce off-design efficiency and can modestly limit flow as head increases [18], [19], [20]. Mitigation strategies such as inter-stage baffle plates and inducer-type guide vanes that moderate pre-swirl can reduce losses and further improve head and efficiency at design conditions. Consequently, the series configuration provides a practical solution for applications requiring higher lifting capacity, trading some flow capacity and efficiency for head enhancement [18], [19], [20].

3.5 Implications for Practical Applications

The results of this study have practical implications for the design and operation of centrifugal pump systems, particularly in applications where higher heads are required. The use of a series pump configuration provides a viable solution for overcoming the head limitations of a single pump, making it suitable for industries and regions where water needs to be lifted to greater heights, such as in high-altitude areas or in large-scale industrial processes.

However, the slight reduction in discharge capacity in the series configuration, particularly at higher pressures, should be considered when designing pump systems. For applications where flow rate is a critical factor, the trade-off between head and capacity should be carefully evaluated to ensure the optimal configuration is chosen for the specific requirements.

4. Conclusion

This study investigates the performance of centrifugal pumps in both single and series configurations, focusing on their head and discharge capacity under varying pressure conditions. The experimental results indicate that connecting centrifugal pumps in series effectively increases the head capacity, with the series configuration achieving nearly double the head of the single pump at higher pressures. Specifically, the series configuration achieved a maximum head of 23.90 meters at 34 psi, compared to 12.65 meters in the single pump configuration at 18 psi.

However, while the head produced by the series configuration was significantly higher, the discharge capacity showed a slight decrease compared to the single pump, particularly at higher pressures. This reduction in capacity is consistent with the principles of centrifugal pump operation, where increased head typically results in a decrease in flow rate. Furthermore, the series configuration experienced additional frictional losses due to the increased length of the piping system, which slightly affected its overall efficiency.

Despite these losses, the series configuration remains a viable solution for applications requiring higher head capacities, especially in situations where a single pump's head capacity is insufficient. The results of this study suggest that the series pump arrangement can be an effective method for overcoming the head limitations of single centrifugal pumps, though careful consideration of the trade-off between head and discharge capacity is necessary when designing pump systems for specific applications.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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