



Optimization of plunger geometry and stroke settings on hydraulic performance of diaphragm metering pumps

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Abstract

This study examines the influence of plunger diameter and stroke length on the performance of a hydraulic diaphragm metering pump, focusing on two key indicators: discharge pressure and flow rate. Experiments were conducted with five plunger diameters (7.90–9.00 mm) and three-stroke settings (100%, 75%, and 50%), validated in accordance with API 675 standards. Results show that each 1 mm increase in plunger diameter produced a consistent rise in flow rate across all stroke settings. Linear regression analysis revealed strong correlations, with flow rate increments of 67.54 mL/min per mm at 100% stroke, 60.78 mL/min per mm at 75% stroke, and 25.34 mL/min per mm at 50% stroke. High coefficients of determination (R^2) confirm the robustness and predictive accuracy of these models. In addition to regression analysis, a two-way ANOVA was performed to statistically evaluate the effects of plunger diameter and stroke length, as well as their interaction, on pump performance. The ANOVA results confirmed that both parameters significantly affected flow rate ($p < 0.05$), while discharge pressure was largely unaffected by stroke variation. The optimal configuration was achieved at a plunger diameter of 8.00 mm and 100% stroke, delivering performance that meets API 675 requirements. Importantly, this study proposes a novel validation framework for hydraulic diaphragm metering pumps based on API 675—a gap not fully addressed in prior research. These findings provide practical guidance for improving the efficiency and reliability of pump systems through optimized geometric and operational parameters.

Keywords:

Plunger, hydraulic diaphragm metering pump, discharge pressure, flow rate.

1 Introduction

The hydraulic diaphragm metering pump plays a vital role in fluid transport and metering systems within the petrochemical industry, especially in applications demanding high dosing accuracy, precise additive injection, and stable flow regulation in critical processes [1], [2]. Its ability to maintain consistent flow rates and discharge pressure is essential for ensuring process stability and product quality.

However, during extended operation, hydraulic diaphragm metering pumps are susceptible to performance degradation primarily due to mechanical wear, particularly on critical internal components such as the plunger and seals [3], [4]. Such wear can result in fluid leakage, pressure instability, and fluctuating flow rates, ultimately compromising system efficiency [5], [6]. Recent studies also emphasize the importance of vibration analysis as a diagnostic tool for detecting pump failures in industrial applications; highlighting that pump performance degradation often originates from mechanical looseness and bearing wear [7]. A reduction in system pressure and inconsistent flow directly impacts production effectiveness and may result in significant operational losses.

Despite their widespread industrial application, research investigating the influence of plunger diameter and stroke variations on critical hydraulic parameters such as discharge pressure and flow rate remains scarce [5], [6], [8]. In particular, there is a lack of systematic studies that explore the interrelationship between these variables in hydraulic diaphragm metering pumps, especially under the specific operational conditions typical of the petrochemical industry [6].

Notably, no prior studies have comprehensively investigated the combined effects of plunger diameter and stroke length under controlled experimental conditions, nor validated pump performance in accordance with the widely recognized API 675 standard. This study addresses this research gap by examining how variations in plunger geometry and stroke settings affect key performance metrics, specifically discharge pressure and flow rate.

By analyzing the interaction between geometric parameters and the system's hydraulic response, the results aim to inform the design of more efficient and reliable pumping systems. Experimental findings are benchmarked against API 675 criteria to identify optimal operating conditions that ensure flow stability, pressure consistency, and compliance with industrial performance standards. Furthermore, this study introduces a novel validation framework for hydraulic diaphragm metering pumps based on API 675 standards, which has not been previously established in existing literature. Unlike prior works, our approach systematically examines the combined effects of plunger diameter and stroke variations under controlled experimental conditions, ensuring both scientific rigor and compliance with widely recognized industrial benchmarks.

2 Research methodology

This research adopts an experimental methodology to improve the performance of hydraulic diaphragm metering pumps by modifying key design parameters, specifically, plunger diameter and stroke length in alignment with the API 675 standard. Five plunger diameters (7.90 mm, 8.00 mm, 8.20 mm, 8.50 mm, and 9.00 mm) were evaluated, each combined with three-stroke settings (100%, 75%, and 50%), resulting in 15 distinct test configurations.

Experiments were conducted using an industrial-grade metering pump equipped with a digital stroke control system, a high-precision flowmeter, and a calibrated pressure gauge. The working fluid was a 3.50% phosphate (PO_4^{3-}) solution, circulated in a closed-loop system to replicate stable operating conditions. For each configuration, performance data were collected as the mean of ten repeated trials to ensure measurement consistency and reliability.

Data analysis was conducted to assess the relative influence of each design parameter on overall pump performance. Linear regression analysis and two-way ANOVA were applied to examine both the individual and interaction effects of plunger diameter and stroke length on discharge pressure and flow rate. The experimental results were then used to develop an empirical model describing the relationships between these variables. This model was validated against API 675 criteria and benchmarked with previous studies, thereby emphasizing the novelty and performance improvements achieved. The overall methodological framework is presented in Fig. 1, which illustrates the systematic sequence of experimental procedures and data processing steps.

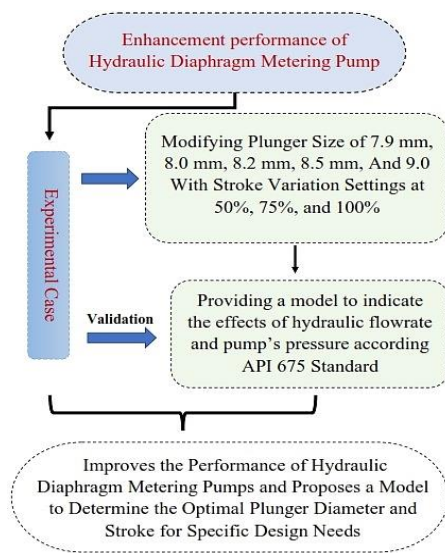


Fig. 1. Methodology.

2.1 Hydraulic diaphragm metering pump

The experimental setup utilized a BL_NOVADOS_H1 hydraulic diaphragm metering pump, which is widely used for chemical dosing applications in the petrochemical industry [9], [10], [11]. The pump features stainless steel (1.4571) housing, a PTFE diaphragm, and a plunger constructed from stainless steel. Its drive system includes a worm gear with adjustable reduction ratios, a splash-type lubrication mechanism, and a stroke adjustment system based on a Z-type (eccentric) crankshaft configuration.

Flow rate regulation is achieved pneumatically, while the drive unit is powered by a constant-speed electric motor. The detailed technical specifications of the pump are presented in Table 1.

Table 1. Standard operational

| Parameter | Value |
|--------------------|----------------------------------|
| Metering accuracy | As good as $\pm 0.50\%$ |
| Fluid name | Phosphate (PO_4^{3-}) |
| Discharge flowrate | 145.50 mL/min |

| | |
|-----------------------------|-----------------------------|
| Discharge pressure (max.) | 60.35 kg/cm ² |
| Plunger diameter | 8.00 mm |
| Plunger material | Stainless steel (ASTM A276) |
| Plunger packing/seal design | Butadiene nitrile rubber |
| Ambient temperature range | From -40 °C to +50 °C |
| Hazardous area | Up to zone 1 IIC T4 |
| Fluid temperature range | From -40 °C up to +150 °C |

The working fluid employed in the experiment was a 3.50% phosphate solution (PO_4^{3-}), selected to simulate real-world operating conditions in petrochemical applications that demand flow stability and corrosion resistance [12], [13]. This test medium was chosen for its relevance in chemical dosing systems, where both dosing precision and material compatibility are essential [14]. A schematic diagram of the hydraulic diaphragm metering pump test platform is shown in Fig. 2.

The experimental procedure commenced by filling the reservoir tank with a 3.50% phosphate (PO_4^{3-}) solution, which was subsequently directed through a valve system and filtered using a Y-strainer to remove particulate contaminants. The fluid then entered the suction side of the hydraulic diaphragm metering pump, passed through a drain valve, and continued into a pulsation damper. The damper was employed to minimize pressure fluctuations and flow instability resulting from the reciprocating motion inherent to positive displacement pumps.

Following damping, the fluid flowed through an isolating valve, which functioned as a safety mechanism to shut off the flow in the event of downstream failure. The flow then proceeded through a flow meter and pressure gauge, used to measure discharge flow rate and pressure, respectively. If excessive pressure is detected, a safety valve is automatically activated to relieve pressure and redirect the fluid back to the pump's suction line. Under normal operating conditions, the fluid was returned to the reservoir tank, thereby completing the closed-loop circulation system.

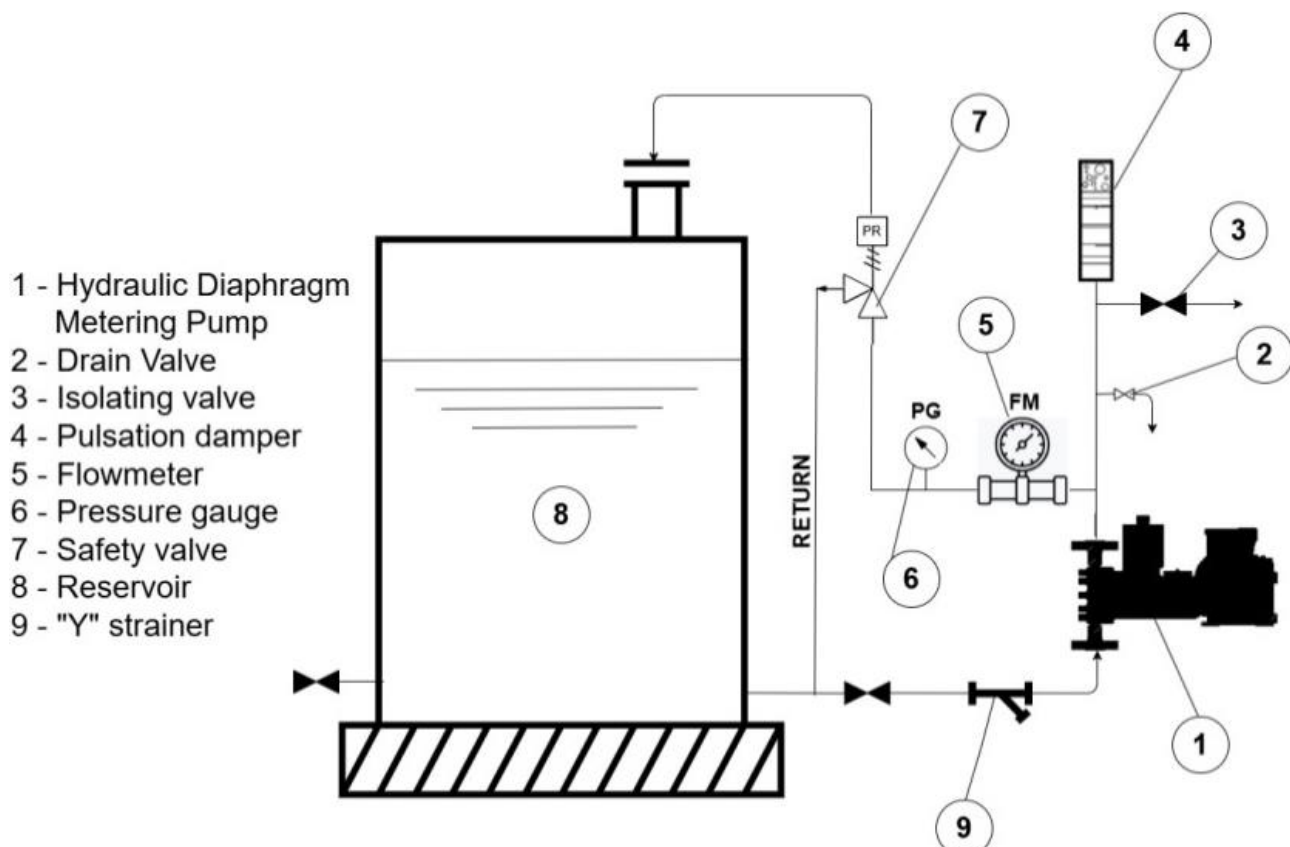


Fig. 2. Schematic diagram of hydraulic diaphragm metering pump test platform.

2.2 Experimental scheme

The experimental setup related to plunger diameter and stroke length variation is shown in Fig. 3 and Fig. 4. By combining the five diameter values with the three stroke settings, a total of 15 distinct test configurations were established.

In this study, plunger diameter and stroke length were defined as independent variables, while the discharge pressure (kg/cm²) and flow rate (mL/min) served as the dependent variables. All tests were conducted under closed-loop conditions to maintain consistent pressure and eliminate the possibility of leakage throughout the experimental process.

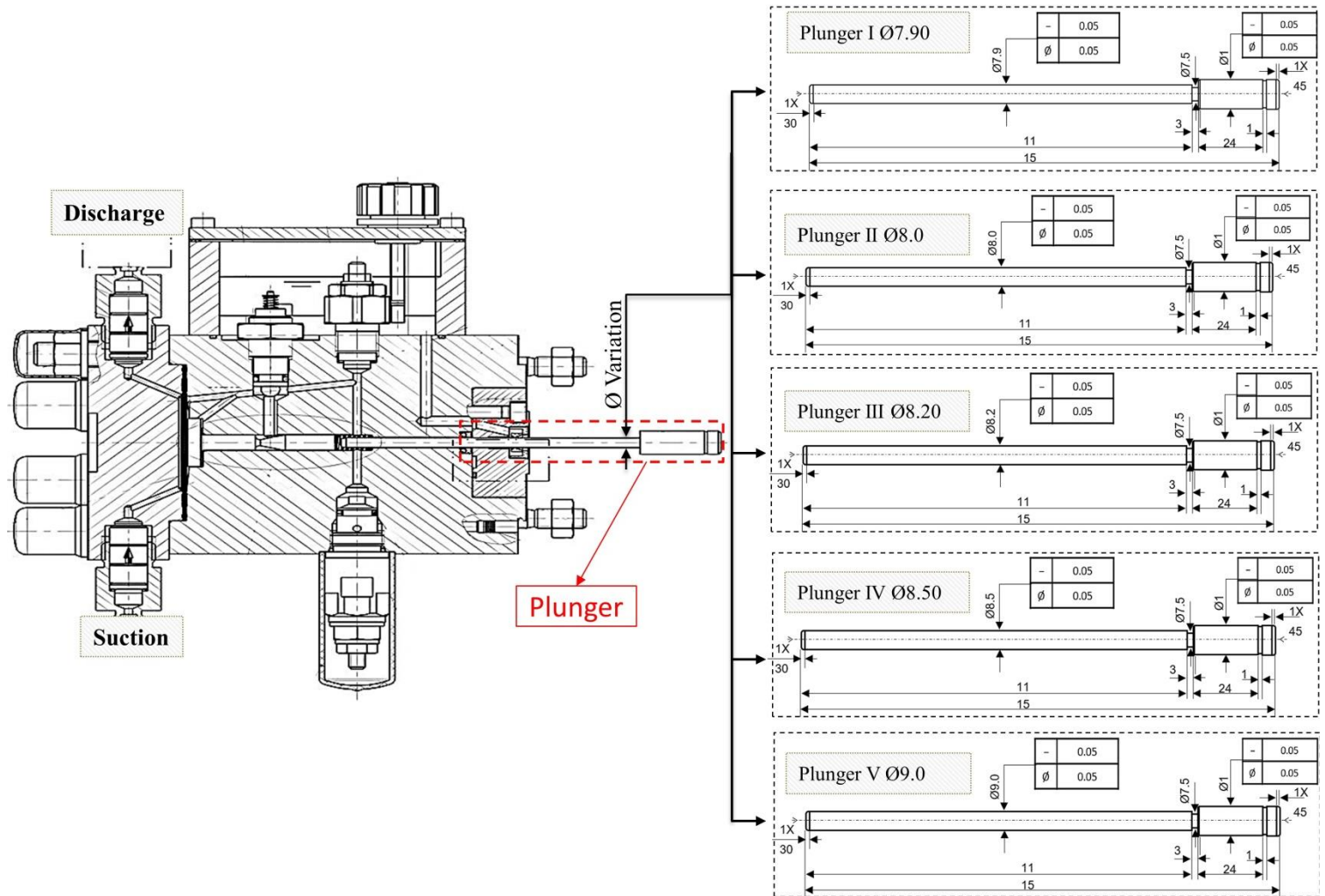


Fig. 3. Experimental configuration illustrating the variation in plunger diameter.

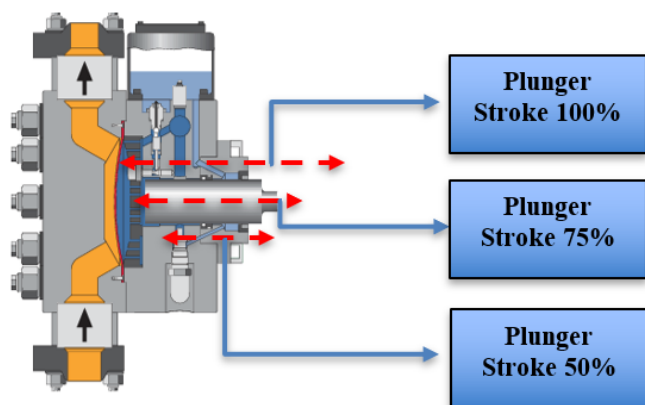


Fig. 4. Experimental configuration for plunger stroke variation.

3 Results and discussion

3.1 Influence of plunger diameter on discharge pressure

The experimental results indicate that increasing the plunger diameter significantly influences pump performance, particularly with respect to discharge pressure [3], [15]. As illustrated in Fig. 5, both theoretical analysis and experimental data confirm that larger plunger diameters reduce the clearance between the plunger and the seal. This reduction enhances the effectiveness of internal sealing, thereby increasing system pressure and minimizing the potential for fluid leakage [8], [16].

In contrast, variations in stroke length exhibited no substantial effect on discharge pressure, indicating that pressure development within the tested conditions is primarily governed by plunger diameter rather than stroke variation [17], [18].

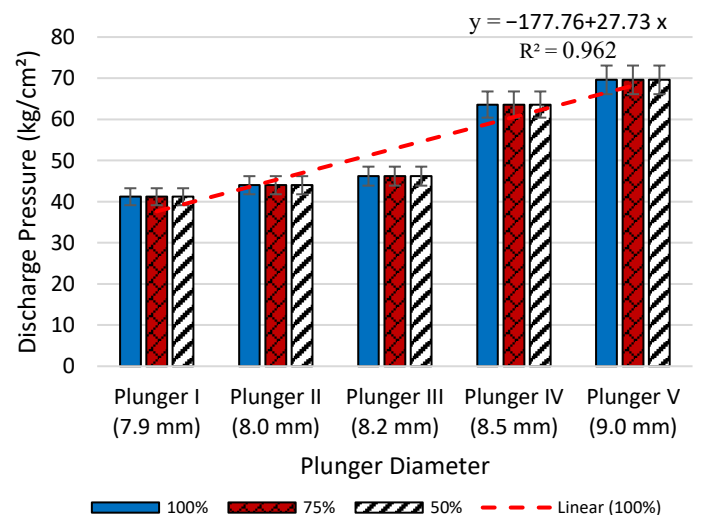


Fig. 5. Discharge pressure profile across different plunger diameter variations.

These findings suggest that adjusting the plunger diameter may serve as an effective interim strategy to compensate for seal degradation, particularly in systems subjected to prolonged operation. The experiments were performed using three-stroke settings of 100%, 75%, and 50% for each of the five plunger diameters (7.90 mm to 9.00 mm), with ten repeated trials per configuration. This repetition was intended to obtain a robust and comprehensive assessment of the direct influence of plunger diameter on discharge pressure in hydraulic diaphragm metering pumps.

The results revealed a consistent increase in discharge pressure with larger plunger diameters, with the effect being most pronounced at the 100% stroke setting. This observation supports the hypothesis that increasing the effective contact area between the plunger and the working chamber improves the pump's ability to maintain stable and efficient pressure [19], [20].

Fig. 5 illustrates the relationship between plunger diameter (x-axis) and discharge pressure (y-axis) across the three-stroke conditions. The data confirm that discharge pressure is predominantly governed by plunger diameter, with stroke variation exerting minimal influence. This suggests that pressure generation is more closely related to the plunger's cross-sectional area than to its stroke length [21].

A linear regression analysis of the data presented in Fig. 5 yields the Eq. (1).

$$y = 27.73 x - 177.76 \quad (R^2 = 0.962) \quad (1)$$

The high coefficient of determination ($R^2 = 0.962$) indicates that approximately 96.20% of the variation in discharge pressure can be attributed to changes in plunger diameter. This strong positive linear relationship confirms that for every 1 mm increase in plunger diameter, the discharge pressure increases by an average of 27.73 kg/cm². These findings highlight plunger diameter as a key design parameter with a direct and significant influence on pressure output in hydraulic metering pumps.

This phenomenon can be physically explained by the concept of the plunger's effective cross-sectional area. As the diameter increases, the volume of fluid displaced per cycle also increases, resulting in a proportional rise in discharge pressure. Consequently, even at reduced stroke lengths—such as 50%—discharge pressure remains relatively stable, as pressure buildup is primarily governed by the plunger's cross-sectional area rather than stroke length.

These findings are further supported by the results of a two-way ANOVA, which examined the influence of plunger diameter and stroke percentage on discharge pressure, as illustrated in Fig. 6.

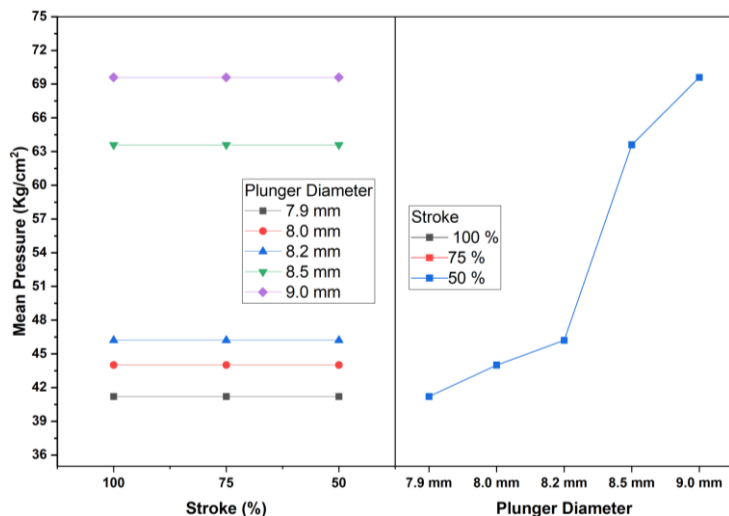


Fig. 6. Two-way ANOVA interaction graph showing effects of plunger diameter and stroke on discharge pressure.

Based on the results of the two-way ANOVA, the plunger diameter was found to have a highly significant effect on discharge

pressure, with an F-value of 4247—far exceeding the critical F-value (2.44)—and a corresponding p-value of 7.30×10^{-141} , which is well below the standard significance threshold of 0.05. This clearly indicates that plunger diameter is the primary factor influencing system pressure.

Conversely, the stroke factor yielded an F-value of 0 with a corresponding p-value of 1.00, indicating no statistically significant effect on discharge pressure. Similarly, the interaction between plunger diameter and stroke resulted in a negative F-value (-2.70×10^{-12}), which is substantially lower than the critical F-value ($F_{crit} = 2.007$), suggesting no significant interaction effect between the two factors on the pressure output.

The interaction plot in Fig. 6 reinforces this observation, as the lines representing different stroke levels (100%, 75%, and 50%) remain nearly parallel and do not intersect. This pattern reflects the absence of interaction effects, implying that the influence of plunger diameter on pressure remains relatively constant regardless of stroke percentage.

These findings underscore the dominant role of the plunger's cross-sectional area in determining pressure, rather than stroke length. Practically, this suggests that adjusting the plunger diameter is a more effective approach for controlling discharge pressure—especially in systems with constant load or fixed operating speed—than modifying the stroke setting.

3.2 Influence of plunger diameter on discharge flow rate

Flow rate testing was conducted using three plunger stroke settings—100%, 75%, and 50%—with each plunger diameter tested in ten repeated trials to evaluate the effect of diameter variation on the performance of the hydraulic diaphragm metering pump. The results indicate that plunger diameter exerts a significant influence on flow rate. The average flow rates recorded during the experiments are presented in Fig. 7. These findings confirm a strong positive linear relationship between increasing plunger diameter and corresponding increases in flow rate.

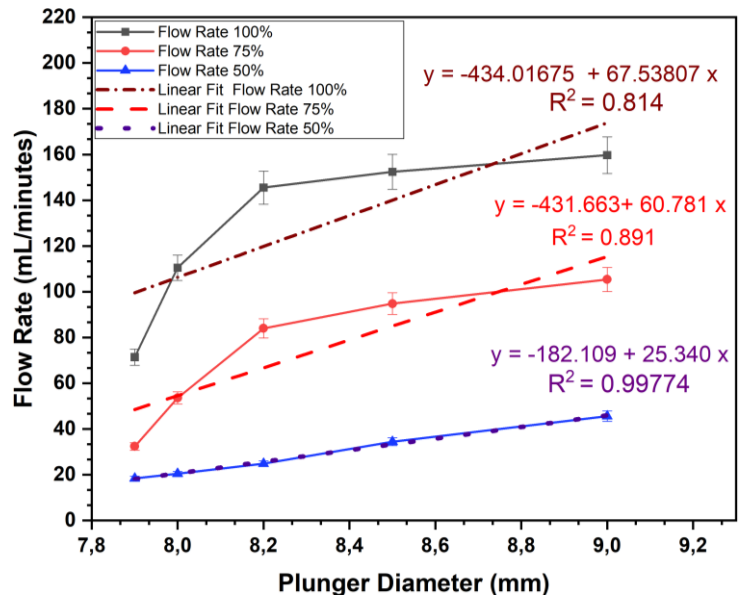


Fig. 7. Effect of plunger diameter variation on discharge flow rate.

The graph in Fig. 7 illustrates the relationship between plunger diameter (x-axis) and flow rate (y-axis), with individual trend lines representing each stroke setting. All trend lines exhibit high linearity, confirming consistent performance behavior. At 100% stroke, the linear regression analysis yields the Eq. (2).

$$y = 67.538 x - 434.016 \quad (R^2 = 0.814) \quad (2)$$

This result indicates that each 1 mm increase in plunger diameter leads to an average flow rate increase of 67.54 mL/min. The coefficient of determination ($R^2 = 0.814$) suggests a moderately strong correlation between plunger diameter and flow rate at full

stroke. Although slight deviations from perfect linearity were observed, the presence of a pulsation damper effectively reduces hydraulic pulsation, contributing to stable and consistent flow behavior throughout the testing process [22].

At 75% stroke, the linear regression analysis yields the Eq. 3.

$$y = 60.781 x - 431.663 \quad (R^2 = 0.891) \quad (3)$$

The results indicate that each 1 mm increase in plunger diameter leads to an increase in discharge flow rate of approximately 60.78 mL/min. Although this value is slightly lower than that observed at full stroke, it still demonstrates a substantial influence of plunger diameter on pump flow performance [23], [22]. Interestingly, the higher coefficient of determination ($R^2 = 0.891$) compared to the 100% stroke condition suggests that the system exhibits more stable and linear behavior at this intermediate stroke setting.

At 50% stroke, the regression analysis yields the Eq. (4).

$$y = 25.340 x - 182.109 \quad (R^2 = 0.99774) \quad (4)$$

The near-perfect coefficient of determination ($R^2 = 0.99774$) indicates an exceptionally strong and stable linear relationship between plunger diameter and flow rate. The regression slope of 25.34 mL/min per mm confirms that the system delivers highly precise flow control under low-stroke conditions. This level of accuracy makes the configuration particularly suitable for applications requiring fine dosing precision, such as chemical injection systems or pharmaceutical-grade processes within the petrochemical industry [22], [24].

Overall, the results confirm that increasing the plunger diameter from 7.90 mm to 9.00 mm leads to a consistent linear increase in flow rate across all stroke settings [22]. Accordingly, adjusting the plunger diameter emerges as an effective engineering strategy for optimizing flow output, particularly in applications requiring higher dosing capacities [5], [10]. The observed linearity across varying stroke levels underscores the versatility of plunger diameter modification as a practical and scalable design parameter for improving hydraulic diaphragm pump performance [5], [11], [25], [26].

The results were corroborated by a two-way ANOVA, which quantitatively evaluated the influence of plunger diameter and stroke length on the flow rate, as presented in Fig. 8.

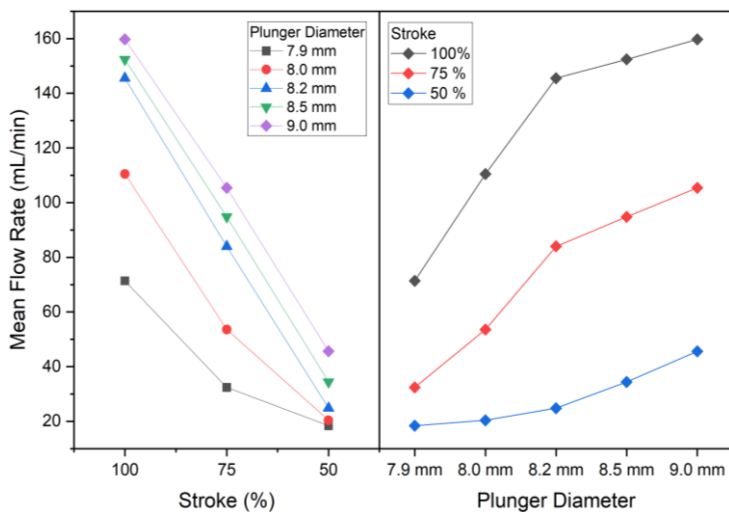


Fig. 8. Two-way ANOVA interaction graph showing effects of plunger diameter and stroke on discharge flow rate.

Two-way ANOVA statistical analysis revealed that both parameters had a highly significant impact on system performance. The main effect of the plunger diameter yielded an F-value of 7128.43, substantially exceeding the critical F-value of 2.44 at the 5% significance level. Similarly, the main effect of stroke length

produced an F-value of 48,277.76, surpassing the critical threshold of 3.06, indicating a strong statistical significance.

Furthermore, the interaction effect between plunger diameter and stroke was also significant, with an F-value of 1741.34, well above the corresponding critical value of 2.01. These results indicate that not only do the individual factors significantly influence the flow rate, but their combined interaction also plays a meaningful role.

This interaction is clearly depicted in the interaction plot shown in Fig. 8, where the lines representing different stroke levels are non-parallel and tend to intersect—indicative of a synergistic interaction. Specifically, the increase in stroke yields a greater contribution to the flow rate when combined with larger plunger diameters. Consequently, optimal pump performance cannot be achieved through the adjustment of a single parameter alone; rather, it necessitates a comprehensive approach that considers the combined effects of both geometric and dynamic variables.

3.3 Performance analysis of hydraulic diaphragm metering pump at different stroke settings

Fig. 9 illustrates the relationship between plunger diameter variation and the average discharge pressure (kg/cm^2) and flow rate (mL/min) recorded during testing of the hydraulic diaphragm metering pump under the maximum stroke setting (100%). Overall, the graph demonstrates a proportional increase in both performance parameters—discharge pressure and flow rate—as plunger diameter increases.

Although both parameters exhibit a clear positive linear trend, the differing slopes of the regression lines reveal varying levels of sensitivity. This suggests that plunger diameter affects flow rate and discharge pressure at different magnitudes. These findings underscore the dual functional role of plunger diameter in simultaneously enhancing pressure stability and volumetric output, particularly under full-stroke operating conditions [6].

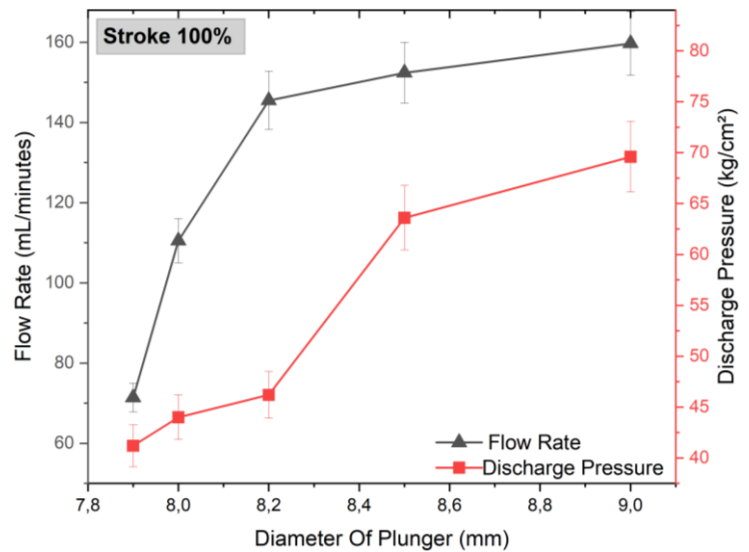


Fig. 9. Pump performance profile at full stroke (100%).

Plunger I (7.90 mm) exhibited the lowest performance, with an average discharge pressure of $41.2 \text{ kg}/\text{cm}^2$ and a flow rate of $71.4 \text{ mL}/\text{min}$, indicating non-compliance with the specified operational standards. In contrast, Plunger II (8.00 mm) demonstrated a marked improvement, achieving a flow rate of $110.5 \text{ mL}/\text{min}$ and an increased discharge pressure of $44.00 \text{ kg}/\text{cm}^2$. This configuration is considered optimal, as all measured performance parameters fall within the operational thresholds defined in both the pump technical manual and the API 675 standard [27], [28], [29].

Plunger III (8.20 mm) delivered the highest compliant flow rate of $145.50 \text{ mL}/\text{min}$, accompanied by a discharge pressure of $46.20 \text{ kg}/\text{cm}^2$. However, this pressure value approaches the upper operational limit of the system, potentially posing a risk of overload in applications with low-pressure tolerance.

Plunger IV (8.50 mm) and Plunger V (9.00 mm) demonstrated continued performance enhancement, with discharge pressures of 63.60 kg/cm² and 69.60 kg/cm², and flow rates of 152.40 mL/min and 159.70 mL/min, respectively. However, both configurations exceeded the system's maximum allowable pressure and were therefore classified as overload conditions. These conditions raise critical concerns regarding excessive backpressure, potential seal degradation, and overall hydraulic system instability [30].

The graph clearly identifies an optimal operating point at a plunger diameter of 8.00 mm (Plunger II), where the system achieves high hydraulic efficiency without exceeding design pressure constraints. Consequently, plunger diameter selection must be guided by a trade-off between maximizing flow performance and maintaining pressure within safe operational thresholds. This balance is essential to ensure long-term system reliability, operational safety, and compliance with industry standards.

Fig. 10 illustrates the relationship between plunger diameter variation and pump performance at the 75% stroke setting. The graph reveals a general trend in which increasing plunger diameter correlates with improvements in both discharge pressure and flow rate, although the magnitude of these improvements is more moderate compared to the results observed under the 100% stroke configuration [28].

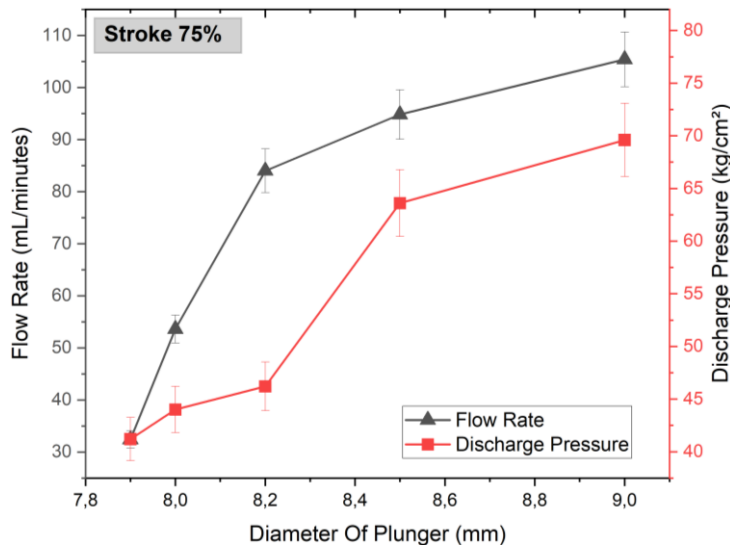


Fig. 10. Pump performance profile at 75% stroke setting.

Plunger I (7.90 mm) demonstrated the lowest performance at the 50% stroke setting, with a flow rate of 32.4 mL/min and a discharge pressure of 41.20 kg/cm², both of which fall significantly below the minimum operational standards. These results indicate that under conditions of reduced stroke and small plunger diameter, the volumetric efficiency of the pump declines sharply. This degradation in performance is likely attributable to increased clearance between the plunger and the sealing surface, which promotes internal fluid leakage and reduces the effective displacement volume [3], [5].

Plunger II (8.00 mm) exhibited a notable improvement in performance, reaching a flow rate of 53.60 mL/min and a discharge pressure of 44.0 kg/cm². However, these values remained below the minimum flow rate required by the process specifications [28]. Plunger III (8.20 mm) further enhanced output, achieving 84.00 mL/min at 46.20 kg/cm², placing it near the efficient operational range—though still not fully meeting the optimal performance criteria outlined in the pump manual.

The highest performance at the 75% stroke setting was recorded for Plunger IV (8.50 mm) and Plunger V (9.00 mm), which yielded flow rates of 94.80 mL/min and 105.40 mL/min, and corresponding pressures of 63.60 kg/cm² and 69.60 kg/cm², respectively [16]. However, both configurations exceeded the maximum allowable discharge pressure specified by API 675, thereby classifying them as overload conditions. These overloads pose potential risks to system integrity, including elevated backpressure, increased seal wear, and

potential mechanical failure, particularly in systems not designed to accommodate such high-pressure loads [6].

As clearly illustrated in the graph, while increasing the plunger diameter enhances both flow rate and discharge pressure, no configuration at the 75% stroke setting fully satisfies both performance requirements simultaneously. Therefore, to achieve optimal hydraulic performance within safe operational limits, it is likely necessary to operate the pump at 100% stroke or alternatively redesign the system to accommodate the increased capacity demands introduced by larger plunger diameters.

Fig. 11 illustrates the relationship between plunger diameter variation and the performance of the diaphragm metering pump at a 50% stroke setting. The graph shows that although increasing the plunger diameter continues to exert a positive influence on both key performance parameters, discharge pressure and flow rate, the absolute values achieved at this reduced stroke are significantly lower than those recorded at the 75% and 100% stroke settings. This indicates a marked reduction in volumetric efficiency and energy transfer per cycle under limited stroke conditions [31].

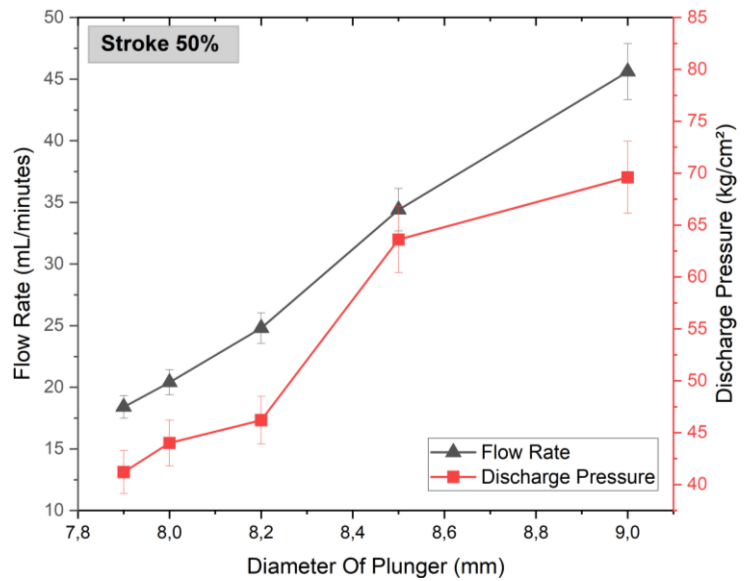


Fig. 11. Pump performance profile at 50% stroke setting.

At a plunger diameter of 7.90 mm (Plunger I), the pump recorded a discharge pressure of 41.20 kg/cm² and a flow rate of only 18.40 mL/min, indicating very low hydraulic efficiency. These findings suggest that under minimal stroke conditions, the displacement volume is insufficient to overcome system resistance, leading to relatively high pressure but inadequate volumetric output. Plunger II (8.00 mm) exhibited a marginal improvement, with a discharge pressure of 44.00 kg/cm² and a flow rate of 20.40 mL/min, although the output remained below the system's minimum required flow rate [26], [28], [31].

A more pronounced performance enhancement was observed with Plunger III (8.20 mm), reaching 24.80 mL/min at a discharge pressure of 46.20 kg/cm². However, the flow rate still did not meet the minimum operational threshold. Substantial gains were achieved with Plunger IV (8.50 mm) and Plunger V (9.00 mm), delivering flow rates of 34.40 mL/min and 45.60 mL/min, respectively, accompanied by steep increases in discharge pressure to 63.60 kg/cm² and 69.60 kg/cm². Despite these improvements, both configurations approached or exceeded the maximum allowable pressure defined by API 675, indicating a potential risk of overpressure if adequate regulation mechanisms are not implemented [31].

The graph clearly demonstrates that under the 50% stroke setting, none of the tested plunger diameter variations were capable of simultaneously meeting both flow rate and discharge pressure performance criteria [32]. Smaller diameters were unable to deliver sufficient flow output, whereas larger diameters resulted in excessive pressure levels, exceeding safe operational limits.

Consequently, operating the pump at 50% stroke is not recommended for applications requiring compliance with industrial standards for both parameters. These findings reinforce the conclusion that full stroke operation (100%), when combined with a moderate plunger diameter, offers a more balanced and optimal configuration—ensuring both volumetric efficiency and system safety [33].

3.4 Identification of the optimal plunger

The experimental results obtained from each test configuration were systematically analyzed and compared against both the operational specifications detailed in the equipment manual (as shown in Table 1) and the technical performance criteria defined by API 675, the internationally recognized standard for metering pump systems.

API 675 emphasizes stringent requirements for accuracy and consistency in fluid metering applications, particularly focusing on two key performance indicators: discharge pressure and flow rate. The compliance and validation outcomes for each plunger configuration are comprehensively summarized in Table 2.

The performance analysis across various plunger diameters and stroke settings revealed that each configuration produced distinct responses in discharge pressure and flow rate—two critical parameters for meeting both manufacturer specifications and the API 675 performance standard. As presented in Table 2, only the configuration using Plunger II (8.00 mm) at 100% stroke successfully satisfied all operational criteria, achieving a discharge pressure of 44.00 kg/cm² and a flow rate of 110.50 mL/min.

Table 2. Performance validation of plunger configurations based on API 675 and equipment manual

| Variation plunger | Configuration | | Experimental | | Standard | |
|-------------------|-----------------------|--------------------|--------------------------------|--------------------|--------------------------------|--------------------|
| | Plunger diameter (mm) | Stroke setting (%) | Pressure (kg/cm ²) | Flow rate (mL/min) | Pressure (kg/cm ²) | Flow rate (mL/min) |
| I | 7.90 | 100% | 41.20 | 71.40 | √ | X |
| I | 7.90 | 75% | 41.20 | 32.40 | √ | X |
| I | 7.90 | 50% | 41.20 | 18.40 | √ | X |
| II | 8.00 | 100% | 44.00 | 110.50 | √ | √ |
| II | 8.00 | 75% | 46.20 | 84.00 | √ | X |
| II | 8.00 | 50% | 44.00 | 20.40 | √ | X |
| III | 8.20 | 100% | 46.20 | 145.5 | √ | √ |
| III | 8.20 | 75% | 46.20 | 84.00 | √ | X |
| III | 8.20 | 50% | 46.20 | 24.80 | √ | X |
| IV | 8.50 | 100% | 63.60 | 152.40 | O | O |
| IV | 8.50 | 75% | 63.60 | 94.80 | O | X |
| IV | 8.50 | 50% | 63.60 | 34.40 | O | X |
| V | 9.00 | 100% | 69.60 | 159.70 | O | O |
| V | 9.00 | 75% | 69.60 | 105.40 | O | X |
| V | 9.00 | 50% | 69.60 | 45.60 | O | X |

Notes:

√ = Meets standard

X = Below standard

O = Overload (exceeds operational limit).

This configuration represents the optimal operating point for hydraulic diaphragm metering pump systems. The findings indicate that a plunger diameter of 8.00 mm offers an ideal compromise between volumetric efficiency and system pressure constraints, delivering a well-balanced solution that ensures performance, reliability, and compliance under real-world industrial conditions [33].

From a fluid mechanics perspective, this operational equilibrium reflects the application of the conservation of momentum and a modified Bernoulli principle that accounts for real-fluid viscosity effects. The optimal plunger geometry minimizes excessive pressure gradients, thereby preventing local turbulence, cavitation, and energy losses due to head loss across internal flow passages.

Meanwhile, Plunger III (8.20 mm) operating at 100% stroke also fulfills the required performance criteria, delivering a discharge pressure of 46.20 kg/cm² and a flow rate of 145.50 mL/min, nearing the upper operational thresholds specified in the equipment manual. However, this configuration may subject the system to potential overload conditions under variable demand scenarios, making it more appropriate for installations with high pressure tolerance and advanced pulsation control mechanisms.

In contrast, Plunger I (7.90 mm) and the lower stroke settings of Plungers II and III exhibit suboptimal performance, particularly in terms of flow rate, which remains below the minimum operational threshold. This inadequacy is likely due to increased clearance between the plunger and the seal, resulting in internal leakage and pressure losses. These performance degradations are associated with non-uniform pressure distributions around the sealing interfaces and elevated shear stress, both of which adversely impact the pump's hydraulic displacement efficiency [11], [34].

Furthermore, Plunger IV (8.50 mm) and Plunger V (9.00 mm) consistently exceed the safe operational limits for both discharge pressure and flow rate, regardless of stroke setting. This over performance is primarily attributed to a reduced working chamber volume, which generates excessive vacuum effects, elevates backpressure, and poses a risk to overall system integrity. Under unsteady flow conditions, these configurations may also induce acoustic resonance phenomena within the pulsation damper, leading to harmonic pressure oscillations. Such oscillations can significantly accelerate mechanical wear, increase fatigue loading on internal components, and ultimately compromise long-term pump reliability [32], [33], [35].

Taken together, these findings underscore the importance of plunger diameter selection as a critical design parameter that must consider not only the required flow capacity, but also pressure stability, flow field behavior, and the mechanical constraints of the pumping system. Based on a comprehensive evaluation of all performance metrics, the 8.00 mm plunger operating at 100% stroke is recommended as the most efficient and reliable configuration, effectively satisfying both technical standards and industrial process requirements. Alternatively, the 8.20 mm plunger at full stroke may be considered for applications requiring higher discharge pressure and increased flow rate. This configuration delivers enhanced output while remaining within the acceptable operational limits specified by API 675, making it suitable for high-demand or pressure-tolerant systems.

4 Conclusions

This study demonstrated that both plunger diameter and stroke length are critical determinants of hydraulic diaphragm metering pump performance, particularly in relation to flow rate and discharge pressure. Experimental results confirmed that larger plunger diameters significantly enhance displacement capacity and pump output, producing a strong linear relationship with flow rate. In contrast, stroke length strongly influenced volumetric throughput but had little effect on discharge pressure, highlighting its role in dosing control rather than pressure generation. These results were statistically validated by two-way ANOVA, confirming the significant main effects and interactions between the two parameters. The optimal configuration was identified at a plunger diameter of 8.00 mm and 100% stroke, delivering an average discharge pressure of 44.00 kg/cm² and a flow rate of 110.50 mL/min, fully compliant with API 675 standards. Alternatively, an 8.20 mm plunger at full stroke achieved a higher dosing capacity of 145.50 mL/min with a discharge pressure of 46.20 kg/cm², making it suitable for high demand applications while maintaining reliability and compliance. Overall, the results confirm that plunger diameter is the dominant factor influencing discharge pressure, while stroke length primarily governs flow rate. Their combined effect significantly impacts overall pump performance, as verified by two-way ANOVA, making the 8.20 mm configuration particularly suitable for high-demand,

pressure-tolerant systems without compromising system reliability or compliance with industrial standards.

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