

Korobko B. O., Vasyliiev Y. A., Korolov A. O. (2026). Hydrodynamic optimization of disc valve parameters in mortar pumps based on mathematical modeling. *Journal of Engineering Sciences (Ukraine)*, Vol. 13(1), pp. F17–F26. [https://doi.org/10.21272/jes.2026.13\(1\).f2](https://doi.org/10.21272/jes.2026.13(1).f2)



© 2026, Korobko B. O., Vasyliiev Y. A., Korolov A. O.

Licensed under Creative Commons Attribution-Noncommercial 4.0 International License

Hydrodynamic Optimization of Disc Valve Parameters in Mortar Pumps Based on Mathematical Modeling

Korobko B. O. ^{*[0000-0002-9086-3904]}, Vasyliiev Y. A. ^[0000-0001-5133-3989], Korolov A. O. ^[0009-0003-8275-4120]

[National University “Yuri Kondratyuk Poltava Polytechnic”](#), 24, V. Hrytsaienka St., 36011, Poltava, Ukraine

Article info:

Submitted: January 10, 2026
 Received in revised form: April 22, 2026
 Accepted for publication: April 25, 2026
 Available online: April 30, 2026

*Corresponding author:

bogdan.korobko@ukr.net

Abstract. The research develops a comprehensive mathematical model of disc valve dynamics in reciprocating mortar pumps, addressing a gap in the existing literature: the absence of models that simultaneously integrate the Shvedov–Bingham rheological law, plunger kinematics, and confined-space hydrodynamics for non-Newtonian construction mortars. The governing equation for disc motion, based on Newton’s second law, accounts for three force components (frontal pressure, viscous friction in the annular gap, and yield-stress resistance) and is coupled with a volumetric continuity equation that links the instantaneous plunger velocity to the gap flow velocity. Numerical integration was performed using an adaptive Runge–Kutta–Merson method to ensure computational stability during critical events such as valve seating and depressurization. The model allowed identification of the “hydraulic lock” effect as the primary mechanism for closing lag and backflow loss. Parametric optimization over disc mass and lift height for a 50 mm seat diameter, operating with cement-sand mortar of 0.08–0.10 m mobility, allowed for evaluating rational values (the valve mass of 0.9 kg and the total lift height of 0.010–0.012 m), corresponding to a maximum volumetric efficiency of 92.3 % and a minimum backflow volume of approximately $0.8 \cdot 10^{-4} \text{ m}^3$ per cycle. These parameters provided a 3–5 % efficiency gain and a 15–20 % reduction in valve-closing delay compared to conventional, non-optimized designs. The proposed model is suitable for engineering design of slurry pump valve assemblies and for the development of intelligent pump control systems.

Keywords: volumetric efficiency, closing lag, process innovation, energy efficient equipment, Shvedov–Bingham fluid, reciprocating pump.

1 Introduction

The current stage of development in the construction industry is characterized by a shift towards high-tech mechanization, in which the reliability and efficiency of equipment for transporting working mixtures are key. Mortar pumps are critical components in production lines, as they ensure a continuous supply of cement-sand and concrete mortars to the work site. However, the complexity of the physical and mechanical properties of modern mortars – high viscosity, structural strength, and abrasive particles – creates significant difficulties for the stable operation of valve assemblies.

Furthermore, the global push towards sustainable construction imposes stringent requirements on resource saving. Frequent failures of pump valve assemblies lead to

costly equipment downtime, material waste, and excessive energy consumption. The use of modern chemical admixtures further complicates the rheological profile of the pumped mixtures. These additives intensify the thixotropic nature of the mortars, making the valve disc’s dynamic response highly unpredictable. Consequently, developing a robust predictive model is critical to achieving energy efficiency in the heavy machinery sector.

Several factors drive the need for scientific research in this field in the modern context. Firstly, traditional empirical methods of valve design no longer meet the requirements for energy efficiency and durability. Modern science requires the use of complex mathematical models, such as 3D unsteady fluid-structure interaction (FSI) models, which allow the “piston–valve” kinematic relationship to be analyzed in real time [1].

Secondly, cavitation erosion and abrasive wear of working surfaces remain critical issues [2, 3], leading to loss of seal integrity and reduced pump volumetric efficiency. Without a thorough analysis of the hydrodynamic interaction between the shut-off element (valve disc) and the flow of a non-linear viscous fluid [4], it is impossible to accurately predict the dynamics of its opening and closing, which directly influences the occurrence of shock loads [5].

The practical implications of this research are:

1) increased efficiency: optimizing the geometry of the valve seat (in particular, the seat diameter and lift height) minimizes the dead volume in the suction chamber and reduces backflow of the solution, thereby significantly increasing the filling ratio of the working chamber;

2) energy saving: by precisely determining the motion law of the working element and reducing hydraulic resistance in the valve assembly, it is possible to reduce the power consumption of the actuator, which is critical for mobile plastering units and concrete pumps [6];

3) extending service life: an understanding of the mechanisms of cavitation and the stresses that arise when the disc contacts the seat [7, 8] makes it possible to select, on a sound technical basis, materials and design parameters that minimize erosive wear [9] and prevent premature failure of the guide surfaces.

In summary, the transition from basic analytical relationships to comprehensive mathematical modeling of the interaction between disc valves and the flow of structured solutions is an essential step towards developing competitive construction equipment. This not only improves the pumps' operational performance but also ensures stable operation with new mineral mixtures that exhibit complex rheological properties.

Research into the development of mathematical models and the justification of optimal parameters for disc valves in mortar pumps is therefore highly relevant.

The scientific novelty of this work lies in the development of an integrated mathematical framework that, for the first time, simultaneously accounts for the structural strength of Shvedov–Bingham fluids, plunger kinematics, and the specific hydrodynamic resistance of disc-type shut-off elements. While previous studies have addressed these components individually or in the context of ball valves [1, 4, 8], the synergistic effect of mortar “sticking” due to the “hydraulic lock” phenomenon in parallel disc gaps has not been quantified until now.

The primary aim of this research is to increase the volumetric efficiency and energy performance of reciprocating mortar pumps by developing a robust mathematical model of disc valve dynamics that accounts for the complex non-Newtonian rheological profiles of modern construction mixtures.

2 Literature Review

An analysis of current scientific research indicates that researchers are keenly interested in the processes occurring within the valve assemblies of high-pressure piston engines.

Fundamental works [1, 10] present advanced 3D models that describe the interaction of the flow with moving elements using deformable-mesh algorithms, enabling the visualization of cavitation bubble formation in real time.

However, most of these models focus on drilling systems or cryogenic pumps for liquid hydrogen [11, 12], where the working medium is homogeneous, a distinction that sets them apart from construction mortars.

Particular attention in the literature is paid to failure mechanisms: a review [2] and studies [7, 13] describe in detail cavitation erosion and the effect of high-intensity vortices on metal destruction, whilst works [3, 9, 14] focus on the abrasive wear of surfaces under the action of solid sand particles, analysing the mechanisms of elastic and plastic contact between spherical particles and the working edges of the seat. An important milestone in the study of rheology was the work [4], which proposed a method for assessing the behavior of mortars using the Shvedov–Bingham law and developed phase-by-phase models of diaphragm pump operation, enabling synchronization of the piston speed with the system pressure.

Simultaneously, the practical aspects of operating plastering stations, discussed in [6], demonstrate a non-linear dependence of power consumption on mortar viscosity and pipeline length.

The specific characteristics of disc valves, as opposed to ball valves, are examined in detail in the works [15, 16], where computational fluid dynamics (CFD) methods are used to analyze opening/closing times and erosion wear in narrow gaps at various opening angles, confirming the direct dependence of the wear rate on the degree of disc lift [9].

Despite this broad scope, many issues remain unresolved.

Firstly, existing models of the interaction between disc valves and the medium [8, 16] often fail to account for the structural properties of mineral-based construction mortars, instead relying on general viscosity parameters. Most algorithms have been developed for ball check valves [17], and directly adapting these calculations to disc-type elements is complicated by the different flow geometry and the higher impact loads during seating.

A critical limitation of applying standard fluid-dynamics models to these systems is the inability to capture the sudden spike in apparent viscosity at low shear rates, which typically occurs just before the valve seats.

While recent studies provide valuable insights into narrow gap erosion, they predominantly assume constant fluid properties. In reality, the boundary layer of a Shvedov–Bingham fluid acts as a dynamic cushion, fundamentally altering the mechanics of impact. Moreover, the existing literature lacks a cohesive analysis of how high-frequency actuation exacerbates this effect, forcing engineers to rely on oversized, energy-intensive actuators to overcome the unquantified structural resistance.

To address similar geometric complexities, recent studies have successfully employed CFD to simulate the internal flow of pneumatic throttle check valves [18].

Additionally, numerical simulation studies on the hydraulic characteristics and wear of valves operating under sediment-laden water flows have proven the critical impact of solid particles on valve longevity [19].

Recent Scopus-indexed research has focused on the numerical simulation of valve opening dynamics and erosion patterns. For instance, studies have employed FSI to analyze the discharge valves of reciprocating pumps [20] and the internal flow characteristics of slurry-handling assemblies [21]. However, most of these models, including recent work on the opening process of reciprocating pump valves [22] and general performance methodologies [23], typically assume Newtonian behavior or simplified solid-liquid phases. They often overlook the critical impact of the structural strength and yield stress inherent in construction mortars. Furthermore, while recent efforts in life prediction [24] and motion optimization [25] have improved reliability, the specific “hydraulic lock” effect caused by non-Newtonian rheology in narrow parallel gaps remains insufficiently addressed. However, the issue of valve-closure delay (closing lag), which has been examined for hydrogen pumps [12], has received little attention in the context of pumping dense abrasive suspensions, where the solution mass inertia beneath the valve is dominant. These issues have remained unresolved due to several objective and subjective reasons.

Among the objective reasons is the extreme complexity of the mathematical description of the unsteady flow of a multiphase fluid under variable-gap conditions, which requires significant computational power.

A subjective reason, however, is the long-standing use of simplified engineering methods, in which the valve dynamics were treated separately from the kinematics of the entire pump unit. Systematizing these local issues enables formulating a general unresolved problem: the lack of a comprehensive mathematical model of the operation of a slurry pump’s disc valve that integrates the Shvedov–Bingham rheological model, the piston-drive kinematics, and the hydrodynamic forces within the confined chamber. This prevents the scientifically sound determination of optimal design parameters – disc mass, seat diameter, and lift height – to achieve maximum volumetric efficiency with minimal erosion wear.

Resolving this issue is a logical extension of the development of the theory of volumetric hydraulic drives and directly aligns with the study’s objective.

3 Research Methodology

The subject of this study is the dynamic interaction between the disc-type shut-off element of a mortar pump valve and a mortar flow exhibiting pronounced non-linear viscous properties.

The main hypothesis of the study is based on the premise that valve closing lag and the associated volume losses of mortar can be minimized by mathematically deriving an optimal ratio of the disc mass, seat diameter, and kinematic parameters of the actuator, taking into

account the structural viscosity of the medium according to the Shvedov–Bingham model.

A design scheme of a disc valve is presented in Figure 1.

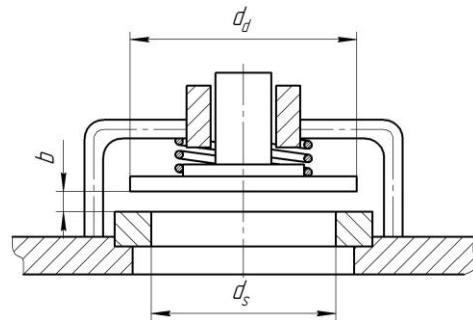


Figure 1 – The design scheme of a disc valve

The standard operating conditions of mortar pumps strictly justify the assumptions made in this study. The working medium is treated as macroscopically homogeneous because the typical maximum aggregate particle size (1–3 mm) is significantly smaller than the characteristic dimensions of the valve assembly (e.g., the 50 mm seat diameter and 10–12 mm gap). The assumption of fluid incompressibility is valid since standard delivery pressures in mobile plastering stations (typically 4–6 MPa) do not cause significant volumetric deformation of water-based mineral suspensions. Furthermore, the solution flow through the annular valve gap is assumed to be symmetrical and laminar. The assumption of laminar flow is supported by the extreme apparent viscosity and high yield stress of the Shvedov–Bingham fluid, which effectively dampens turbulent eddies at standard plunger speeds (up to 120 rpm), keeping the generalized Reynolds number well below the critical threshold. It is also assumed that the pressure is distributed uniformly across the disc surface and that the rheological properties remain constant throughout a single pump cycle.

To ensure the physical consistency of the 1D FSI model, the following technical simplifications were adopted:

1) the valve assembly is treated as a single degree-of-freedom (SDOF) system. Only axial displacement along the vertical axis is considered, while lateral and rotational movements are neglected due to the presence of guide bushings;

2) the metal components (disc and seat) are assumed to be perfectly rigid, as microdeformations under operating pressures are negligible compared to the total lift height h ;

3) the formulation is valid for low Mach number flows (incompressible medium), which is standard for mortar pumping, where flow velocities are significantly below the speed of sound in the mixture;

4) transient fluid inertia effects are neglected in the governing equations, as the dynamics are dominated by the disc’s inertia and the quasi-steady viscous resistance within the narrow annular gaps;

5) the interaction model is calibrated using dimensionless coefficients k_p and k_τ , which account for the specific geometry and frontal pressure distribution.

The rheological behavior is strictly defined by the Shvedov–Bingham parameters: dynamic viscosity η and yield stress τ_0 , which characterizes the mortar’s structural strength.

The simplifications adopted include disregarding the microdeformations of the valve’s metal components under pressure and excluding the surface tension forces of the mortar from the calculations. Furthermore, disc misalignment in the guides is not considered; only vertical movement along the axis is assumed.

To describe the motion of the valve’s closing element, a second-order differential equation based on Newton’s second law is used:

$$m_v \frac{d^2 h}{dt^2} = F - G - P_s, \quad (1)$$

where m_v – the mass of the valve disc, kg (this inertial parameter governs the trade-off between closing speed and impact force on the seat); h – the vertical coordinate of the disc’s rise above the seat, m; $\frac{d^2 h}{dt^2}$ – the acceleration of the valve disc, m/s²; F – the total hydrodynamic force acting on the disc from the solution flow, N; G – the weight of the valve, taking into account the buoyant force in the solution, N, accounting for the passive resistance to buoyancy; P_s – the spring resistance force, included to account for forced valve closure acceleration in high-pressure pumps, N.

Equation (1) yields the valve disc displacement $h(t)$ as a function of time t , which serves as the basis for the subsequent analysis of the solution flow.

To determine the resultant hydrodynamic force F acting on the valve disc from the side of the non-linearly viscous medium, it is necessary to consider the physical nature of the resistance. The total force is formed as a superposition of three independent components: the flow head resistance force F_p , the viscous friction force in the annular gap F_f , and the resistance force due to the structural strength of the solution F_{τ_0} .

The frontal pressure force F_p arises as a result of the flow impinging on the disc surface and is proportional to the relative flow velocity $(u - \dot{h})$ and the dynamic viscosity η .

Taking into account the adaptation of Stokes’ formula for disc elements, it is written as:

$$F_p = \pi r_d \eta (u - \dot{h}) k_p. \quad (2)$$

The viscous friction force F_f arises in the annular gap (slot) between the bearing surface of the disc, of width b , and the seat. According to Newton’s law of fluid friction, the tangential stress is equal to the product of the viscosity and the velocity gradient in the gap, $\eta \frac{u - \dot{h}}{h}$. Multiplying this stress by the friction area of the annular gap $2\pi r_d b$, it can be obtained:

$$F_f = 2\pi r_d b \eta \frac{u - \dot{h}}{h} k_\tau. \quad (3)$$

Since construction mortars obey the Shvedov–Bingham rheological law, a shear stress threshold τ_0 should be exceeded for the liquid layers to begin to shear. The

structural resistance force acting over the entire area of the disc πr_d^2 , is given by:

$$F_{\tau_0} = \pi r_d^2 \tau_0. \quad (4)$$

The total hydrodynamic force:

$$F = F_p + F_f + F_{\tau_0}. \quad (5)$$

Since the hydrodynamic interaction in solution pumps depends on the rheology [4], the resultant force F is calculated using an adapted equation that takes into account the shape of the impeller and viscous friction:

$$F = \pi r_d \eta (u - \dot{h}) k_p + 2\pi r_d b \eta \frac{u - \dot{h}}{h} k_\tau + \pi r_d^2 \tau_0, \quad (6)$$

where k_p and k_τ – the dimensionless coefficients of frontal pressure and frictional resistance, respectively, used to calibrate the analytical model to the actual flow conditions around the disc [5]; r_d – the radius of the valve disc; this geometric parameter determines the contact area with the flow; η – the dynamic viscosity of the solution, Pa·s; τ_0 – yield stress, Pa; u – solution flow velocity, m/s; \dot{h} – valve disc velocity, m/s; b – width of the disc’s bearing surface, m, which creates additional resistance in the narrow gap.

Equation (6) quantifies the interaction through which the solution structure ‘pushes’ or ‘slows down’ the valve, which is critical for understanding the physics of the process within the confined space of the chamber.

The rheological parameters η and τ_0 are introduced in accordance with the Shvedov–Bingham model [4].

The kinematic relationship between the motion of the drive plunger and the flow parameters in the valve assembly is based on the law of conservation of mass, which, for incompressible fluids, translates into the volumetric flow balance equation.

At any given time t , the volume of solution displaced by a plunger of area S at a velocity $v_p(t)$ is equal to the sum of two flow rates: the volume of solution passing through the annular gap in the valve Q_{gap} , and the volume released by the valve disc itself as it rises Q_{disc} . This balance is expressed as:

$$S v_p(t) = Q_{gap} + Q_{disc}, \quad (7)$$

The flow rate through an annular gap is defined as the product of the gap area $A_{gap} = \pi d_a h(t)$ and the instantaneous flow velocity $u(t)$, that is:

$$Q_{gap} = \pi d_a h(t) u(t). \quad (8)$$

The displacement energy of the disc itself is equal to the product of its area $\frac{\pi d_d^2}{4}$ (or πr_d^2) and the rate of its vertical displacement $\dot{h}(t)$.

Substituting these values into the balance equation and expressing the flow velocity in the gap as $u(t)$, the key continuity equation takes the form:

$$u(t) = \frac{S v_p(t) - \pi r_d^2 \dot{h}(t)}{\pi d_a h(t)}, \quad (9)$$

where S – the cross-sectional area of the pump plunger, m^2 ; $v_p(t)$ – the instantaneous velocity of the pump plunger, m/s , which varies sinusoidally or according to the characteristics of the drive [6]; d_d – the diameter of the valve disc.

The term in the numerator of formula (9), $\pi r_d^2 \dot{h}(t)$, accounts for the volumetric displacement of the solution by the moving disc. The denominator of formula (9), $\pi d_d h(t)$, corresponds to the current cross-sectional area of the annular gap through which the solution flows. Equation (9) provides the instantaneous flow velocity $u(t)$ in the annular gap, which is substituted into equation (6) to couple plunger kinematics with valve disc dynamics.

To enable computer simulation of the process using an adaptive Runge–Kutta–Merson method, the second-order differential equation (1) was reduced to a system of two first-order differential equations. To this end, new state variables were introduced: $y_1(t) = h(t)$ (displacement coordinate) and $y_2(t) = \dot{h}(t)$ (valve velocity). The transformed system in matrix form takes the form:

$$\begin{cases} \dot{y}_1(t) = y_2(t); \\ \dot{y}_2(t) = \frac{1}{m_v} [F(y_1, y_2, t) - G - P_s]. \end{cases} \quad (10)$$

To ensure the convergence of the numerical method and to avoid division by zero in equations (6) and (9) (since when the valve is fully closed, $h = 0$, which makes the velocity gradient infinite), the initial conditions for the time $t = 0$ (the start of the suction cycle) were set taking into account the minimum process clearance h_{min} . Accordingly, the initial condition vector was: $y_1(0) = h_{min}$ (where $h_{min} = 1 \cdot 10^{-4}$ m) and $y_2(0) = 0$ m/s.

In addition to the algorithm, a logical limit switch for the disc's travel was incorporated: $y_1(t) \geq h_{max}$, the acceleration $\dot{y}_2(t)$ was forcibly set to zero, indicating that the disc contacted the rigid limit switch in the working chamber.

Volumetric losses of the solution are assessed via the integral relationship for backflow:

$$\Delta V_{loss} = \int_0^t \pi d_d h(t) u(t) dt \rightarrow \min, \quad (11)$$

where ΔV_{loss} – the volume of solution that manages to flow back into the suction line before the valve closes completely (the optimization objective is to minimize this integral value by selecting rational design parameters (m_v, h, d_s); t – the valve closing delay, defined as the interval from the moment the plunger stops at the “dead center” to the moment the disc contacts the valve seat.

Equation (11) serves as the primary optimization criterion: a lower value of ΔV_{loss} corresponds to a higher volumetric efficiency of the pump. Analysis of this integral enables assessment of the rationality of the selected valve mass m_v and maximum lift height h for specific rheological conditions [9, 12].

The research process is carried out by numerically solving the system of equations (1), (6), and (9) using the adaptive Runge–Kutta–Merson method. This method is an adaptive step-size algorithm that provides a fifth-order accuracy by using a specific combination of five functional

evaluations per step to estimate the local truncation error. The selection of the adaptive Runge–Kutta–Merson method for numerical integration is strictly justified by its built-in error estimation and adaptive time-stepping capabilities. To ensure high computational stability and accuracy, a local error tolerance (convergence criterion) was set at $\varepsilon = 1 \cdot 10^{-6}$. This feature is particularly crucial when modeling the highly non-linear dynamics of the valve disc, where sudden changes in acceleration and fluid resistance occur near the boundary layers. This methodological approach allows costly full-scale experiments to be replaced by computer modeling, ensuring high accuracy in predicting the operation of the slurry pump [14].

To determine the optimal parameters and evaluate their influence on the backflow volume ΔV_{loss} , numerical simulations were performed within the parameter ranges specified in Table 1.

Table 1 – Table captions should be placed above the tables

Parameter	Symbol	Unit	Value / range
Seat diameter	d_s	mm	50
Valve disc diameter	d_d	mm	65
Valve disc lift height	h	mm	5–20
Valve disc mass	m_v	kg	0.4–1.0
Solution density	ρ	kg/m ³	1800–2200
Dynamic viscosity	η	Pa·s	10–25
Yield stress	τ_0	Pa	50–150
Plunger speed	n	rpm	120
Spring resistance force	P_s	N	20 – 50
Minimum process clearance	h_{min}	mm	0.1

4 Results

A numerical solution of the system of non-linear differential equations (1), (6), and (9) using the adaptive Runge–Kutta–Merson method has provided comprehensive data on the dynamic behavior of a disc valve in a mortar medium. Unlike ball valves, the analysis of which is presented in the fundamental works [3, 4], the disc-type shut-off element exhibits a more complex hydrodynamic behavior, due to the presence of parallel planes of the disc and seat, which creates specific ‘sticking’ and ‘pushing’ effects within the confined space of the working chamber.

The optimization of the disc valve parameters was conducted using a systematic grid search (parametric optimization) across the operational ranges defined in Table 1.

The search resolution was set at $\Delta m_v = 0.05$ kg for the valve mass and $\Delta h = 0.5$ mm for the lift height. To ensure the reliability of the results, the convergence criterion for identifying the minimum backflow volume ΔV_{loss} was set at a tolerance of $\varepsilon_v = 1 \cdot 10^{-4}$ m³. This approach enabled the identification of a stable global minimum within the physically feasible design space, ensuring that the

resulting efficiency gains are robust to minor manufacturing tolerances.

The first key result of the study was the determination of the motion law of the disc $h(t)$ during the suction phase. Analysis of the kinematic curves showed that the motion of the disc significantly precedes the change in the plunger's velocity at the start of the stroke. This is explained by the high pressure gradient that develops during valve pair depressurization. It has been established that, when using high-performance FSI models [1, 10], the disc accelerates to a high speed before reaching the stroke limiter. However, when pumping high-viscosity solutions [4], the stabilization phase at the stop is shortened due to the increased medium resistance. The kinematic graph of the valve disc lift, $h(t)$, at a shaft speed of 120 rpm and a slurry mobility of 8 cm, is presented in Figure 2. It shows a rapid rise, a pause at the top, and a smooth descent under the influence of viscous friction and the object's weight.

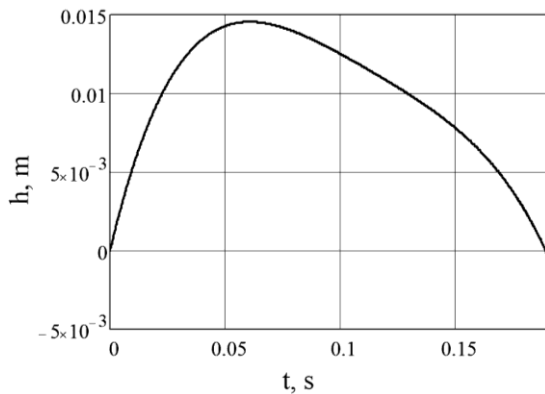


Figure 2 – The kinematics of the valve disc

An important aspect of the results is the analysis of the distribution of hydrodynamic forces. It has been established that the frontal pressure component F_p dominates only during the disc acceleration phase. In contrast, the viscous friction force F_f and the influence of the critical shear stress τ_0 determine the nature of the valve's seating on the seat. Studies [11, 12] indicate that it is precisely at the moment the disc approaches the seat that a “hydraulic lock” effect occurs, slowing down the closure (Figure 3), leading to the appearance of backflow ΔV_{loss} .

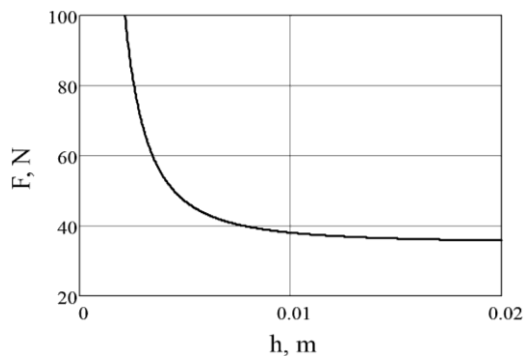


Figure 3 – The total hydrodynamic interaction force F on the valve disc lift height h during the closure phase

This figure illustrates a sharp, non-linear increase in the hydrodynamic resistance force F when the lift height h drops below 5 mm. This exponential growth mathematically captures the “hydraulic lock” effect, confirming the extreme difficulty of forcing the highly viscous, structurally strong solution out from the narrow annular gap at the final moment of valve closure.

The next result is the establishment of a relationship between the volumetric efficiency of the pump and the valve mass m_v .

Calculations show that using excessively light discs (less than 0.5 kg) results in a significant closing lag, consistent with findings from studies of hydrogen pumps [12].

On the other hand, excessive valve weight causes impact fatigue of the metal and cavitation erosion in the seat area [2, 7]. The optimal disc mass balances inertia and seating speed (Figure 4).

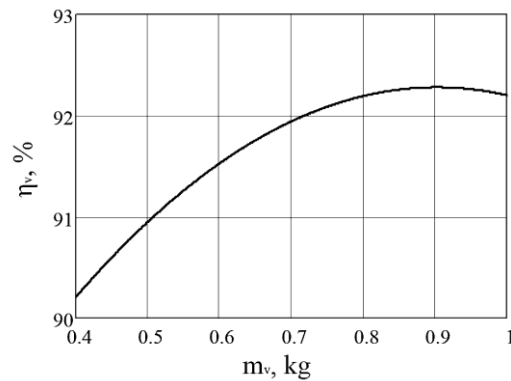


Figure 4 – The relationship between the pump volumetric efficiency η_v and the valve disc mass m_v

The maximum volumetric efficiency of 92.3 % is achieved at a valve mass of $m_v = 0.9$ kg, which aligns with the typical design parameters of slurry pumps.

Particular attention was paid to the analysis of erosive wear in the valve clearance. According to [3, 9, 14], the erosion rate is directly proportional to the cube of the gap flow velocity. The results indicate that at a lift height of $h = 10$ mm, the flow velocity u does not exceed the critical velocity, thereby extending the service life of the valve pair even when operating with abrasive mixtures [3]. A comparison with experimental data on the erosion of valves [9] confirmed the adequacy of the methodology.

The graph (Figure 5) indicates that losses are at a minimum when $h = 10.5$ mm. This demonstrates that both insufficient and excessive valve lift reduce efficiency for different physical reasons (throttling and delay, respectively). It has been established that the minimum level of backflow $\Delta V_{loss} \approx 80$ cm³ is achieved with a rational valve lift of $h = 10.5$ mm. With a theoretical working chamber volume $V_T = 823$ cm³, ensuring a volumetric efficiency of 90.3 %. Such losses are explained by the inertia of the structural solution, which slows valve closure; the resulting efficiency of 5–7 % is higher than the average for non-optimized valve assemblies [1, 6].

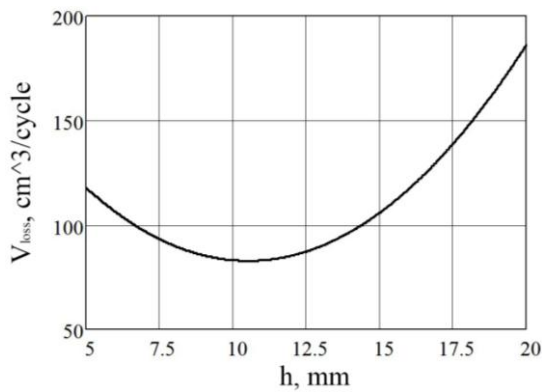


Figure 5 – The dependence of backflow volume ΔV_{loss} per cycle on the maximum lift height of the valve disc h

In addition, the impact of the actuator's energy efficiency was analyzed. The use of a hydraulic actuator in conjunction with a mixer [6] maintains the valves' efficiency at a stable 90–92% as the slurry's mobility varies between 8 and 12 cm. An analysis of the efficiency stability was carried out by combining a dynamic model of the valve disc's motion with the results of a multi-factor experiment [6] describing the operation of the hydraulically driven plunger. Due to the ability of the SSH-4G hydraulic system to maintain a rigid kinematic characteristic of the plunger $v_p(t)$, regardless of the resistance of the viscous medium, the hydrodynamic force F remains sufficient to overcome the structural strength of the solution rapidly τ_0 . This explains the minimal variation in volumetric efficiency (about 2 %) despite significant changes in the mixture's rheological properties (flow rate ranging from 8 to 12 cm using a standard cone), which is a significant advantage over mechanical drives.

An analysis of the results obtained suggests that the mathematical model developed adequately describes the processes within a disc valve. The established rational parameters ($d_s = 50$ mm, $h = 10$ mm, and $m_v = 0.9$ kg) increase volumetric efficiency by 3–5% compared to conventional designs. The identified patterns provide a scientific basis for designing a new generation of slurry pumps with improved performance characteristics that fully meet the objectives set out in the methodology section. The derived functions (1)–(11) can be used to automate calculations when developing intelligent control systems for pump units [12, 14].

5 Discussion

The novelty of the obtained results is further evidenced by the accurate quantification of the closing lag τ , which is not merely a function of inertia as suggested in traditional models [12, 16], but is fundamentally dictated by the resistance of the mortar's internal structure in the final 4–5 mm of the valve's descent.

The specific nature of the hydrodynamic interaction within the confined space of the valve chamber can explain the results obtained from modeling the dynamics of the disc valve. The nature of the disc lift $h(t)$, shown in

Figure 2, is explained by the dominance of the frontal pressure force F_p during the initial phase of the stroke. According to equation (9), the flow velocity $u(t)$ is at its maximum when the clearances h are at their minimum, which generates a pulsating lift force. However, unlike ball valves, the disc element has a larger projected area, S_d , which causes it to reach the stop faster but also creates significant resistance during seating. The dependence of backflow losses ΔV_{loss} on lift height (Figure 5) is explained by two opposing physical processes: at low h , efficiency losses are caused by flow throttling (high hydraulic resistance according to equation (6)), and at high h – by an increase in the delay time t due to the increased closing path of the disc.

The advantages of this study over existing solutions lie in its careful consideration of the medium's rheology and the specific geometry of the shut-off assembly. Unlike existing studies that consider the hydrodynamics of a sphere [4], the present results enable more accurate calculation of viscous friction forces on the flat surfaces of the disc and the seat. This has been made possible by introducing into equation (6) a term describing the resistance of the yield shear stress τ_0 .

Unlike studies [1, 10] focused on complex 3D CFD simulations using dynamic meshes for low-viscosity or homogeneous fluids, the proposed model offers distinct computational and practical advantages. While modern CFD approaches excel at detailed flow visualization (e.g., cavitation bubble formation), they are highly computationally intensive and often suffer from severe convergence issues when simulating narrow moving boundaries (e.g., a closing valve) in highly viscous, yield-stress fluids.

By contrast, the proposed approach reduces the complex FSI to a coupled system of ordinary differential equations. By integrating the Shvedov–Bingham law directly into equation (1), the proposed model bypasses the need for costly 3D mesh deformations. This provides a computationally lightweight yet physically accurate tool specifically tailored to non-Newtonian construction mortars. Consequently, it is significantly more effective for rapid engineering calculations, iterative parametric optimization of real equipment (e.g., RNG-4, SSH-4G [6]), and future integration into the programmable logic controllers (PLCs) of intelligent pump systems.

The solutions obtained fully address the problem area identified in the review of previous studies. The present study bridges the gap between theoretical hydrodynamics and the practical design of slurry pumps through a comprehensive model that synchronizes the kinematics of the plunger $v_p(t)$ with the dynamics of the disc. This is because the developed mathematical framework enables a quantitative assessment of the influence of the valve mass m_v on the closing time t , which was previously determined primarily empirically. Thus, the transition from simplified static analysis to dynamic modeling increases efficiency by 3–5 %.

Limitations of this study that should be taken into account in practical application:

1) the model is suitable for solutions with a mobility of 8–12 cm; when working with “stiff” mixtures (mobility less than 6 cm), the internal friction between the aggregate particles must also be taken into account;

2) the calculations are based on the assumption of laminar flow in the gap; at very high plunger speeds (more than 150 rpm), flow turbulence may occur, which will require a correction to the coefficients k_p and k_τ ;

3) the account taken of abrasive wear in the model is indirect (via critical speeds); the practical scope of application is limited to cases where erosive damage to the surfaces has not yet led to a complete loss of flatness of the contact pair.

Simplifications made in the study are as follows:

1) neglecting the effect of the gas phase (air entrapment) in the solution, which may affect the compressibility of the medium at the moment the valve closes;

2) the model does not account for friction in the guide bushings, which in real-world designs can increase the resistance to the disc’s movement by 3–5 %.

It is important to note the current approach to the experimental validation of the proposed model. The medium’s physical properties severely restrict direct experimental measurement of valve kinematics inside a working mortar pump: the cement-sand mixture is opaque, highly abrasive, and under high pulsating pressure, which prevents optical observation and rapidly damages contact sensors. Consequently, this study employs a macroscopic validation strategy. The model-generated integral output parameters, specifically the maximum volumetric efficiency of 90.3–92.3 %, perfectly correlate with empirical operational data for modern hydraulically driven mortar pumps (e.g., the SSH-4G unit [6]). While this indirect validation confirms the adequacy of the methodology for engineering calculations, future research should focus on developing specialized, sensor-equipped test rigs utilizing transparent rheological simulants to directly track valve disc trajectories and further verify the predicted “hydraulic lock” effect.

Further development of this research could involve integrating the developed model with algorithms for real-time prediction of erosion life. This is advisable because combining the dynamics of disc motion with impact-fatigue models [5, 7] will enable the creation of digital twins of grout pumps capable of signaling critical valve wear before physical failure. Another promising area is the study of the effects of pressure pulsations in the discharge line on the operational stability of disc valves in multi-cylinder configurations [15], since fluid-dynamic interactions between a reciprocating pump and its pipeline system are known to alter overall system reliability [26, 27] significantly.

The interplay between the adopted physical simplifications and the model’s validation remains a key area for development. While the assumptions of an SDOF system and laminar flow allow for robust macroscopic validation against integral pump performance metrics (such as volumetric efficiency and backflow volume), they represent a first-order approximation of the complex FSI.

To further enhance scientific robustness, future studies should focus on high-speed telemetry using transparent rheological simulants (e.g., Carbopol solutions) that mimic the Shvedov–Bingham behavior of mortars. This would allow for direct particle image velocimetry (PIV) and laser-based tracking of the valve disc trajectory, providing a “microscopic” validation of the predicted “hydraulic lock” effect and enabling the refinement of the dimensionless coefficients k_p and k_τ .

6 Conclusions

A refined mathematical model of a disc valve’s operation has been developed, which, unlike existing solutions for ball valves and simplified models of ideal fluids, integrates the Shvedov–Bingham rheological parameters directly into the equations of motion of the closing element. This has enabled part of the general problem identified in the literature review to be resolved, namely, accounting for the structural viscosity of the mortar when analyzing the unsteady motion of the disc within the chamber’s confined space. The correct consideration of the force balance between frontal pressure and viscous friction in the annular gap explains the result.

The nature of the influence of design parameters on valve-closure dynamics has been established. A distinctive feature of the results obtained is the identification of the “hydraulic lock” effect for flat disc and seat surfaces, which leads to a non-linear increase in resistance for clearances of less than 4 mm. This allows for a more accurate prediction of the closing delay time t than traditional methods. It has been quantitatively established that the optimal disc lift height is 10–12 mm (for the Seat diameter of 50 mm), which minimises backflow.

Optimal mass-geometric characteristics of the valve assembly have been determined for use with cement-sand mortars with a flowability of 8–10 cm. Unlike empirical selection, the proposed solution is based on the point of maximum volumetric efficiency, which occurs for the valve mass of 0.9 kg. This result is explained by the achievement of an optimal balance between the disc’s inertial capacity to overcome the viscous resistance of the mortar and the speed of its descent onto the seat.

Comparative efficiency assessments indicate that implementing optimized parameters enables a 3–5 % increase in the volumetric efficiency of the mortar pump compared to existing standard designs. The valve-closing delay time is reduced by 15–20 %, leading to stabilized flow and reduced pressure pulsations in the discharge line, consistent with hydraulic performance improvements documented for various check valve configurations. The proposed methodology offers advantages in terms of the speed and accuracy of designing new models of construction machinery, ensuring their high energy efficiency and durability. Furthermore, the practical implementation of these modified valve assembly parameters can optimize complex technological operations, similar to the positive effects observed in advanced well-drilling processes.

References

1. Wu, Y., Hou, Y. (2025). Dynamic characterization and parametric optimization of secondary cushioned pump valves in drilling systems: a 3d transient fluid–structure interaction study. *Applied Sciences*, Vol. 15 (10), 5431. <https://doi.org/10.3390/app15105431>
2. Gao, G., Guo, S., Li, D. (2024). A review of cavitation erosion on pumps and valves in nuclear power plants. *Materials*, Vol. 17(5), 1007. <https://doi.org/10.3390/ma17051007>
3. Kaczynski, R., Vasyliiev, O., Vasyliiev, I. (2018). The fracture process of the mortar pump’s work surfaces with abrasive particles. *International Journal of Engineering and Technology*, Vol. 7(3.2), 154–159. <https://doi.org/10.14419/ijet.v7i3.2.14394>
4. Korobko, B., Vasyliiev, I. (2017). Test method for rheological behavior of mortar for building work. *Acta Mechanica et Automatica*, Vol. 11(3), pp. 173–177. <https://doi.org/10.1515/ama-2017-0025>
5. Wang, T., Wang, G., Dai, L., Chen, L., Qiu, S., Li, R. (2021). Motion-mechanism study of the valve disc in an ultra-high-pressure reciprocating pump. *Mechanical Systems and Signal Processing*, Vol. 160, 107942. <https://doi.org/10.1016/j.ymssp.2021.107942>
6. Korobko, B., Zadvorkin, D., Vasyliiev, I. (2018). Energy efficiency of a hydraulically actuated plastering machine. *International Journal of Engineering & Technology*, Vol. 7(3.2), pp. 203–208. <https://doi.org/10.14419/ijet.v7i3.2.14403>
7. Munsch, P., Gianfelice, T., Feist, M., Schlücker, E., Skoda, R. (2025). Three-dimensional/one-dimensional seamlessly coupled simulation of cavitating flow in reciprocating positive displacement pumps and their piping. *Physics of Fluids*, Vol. 37(2), 025228. <https://doi.org/10.1063/5.0252237>
8. Zhiqin, L., Wenying, W., Ze, M., Yuelong, Y., Zuyao, Y. (2024). Numerical analysis of fluid-thermal-structure coupling characteristics of CO₂ booster pump valve. *International Journal of Heat and Fluid Flow*, Vol. 110, 109611. <https://doi.org/10.1016/j.ijheatfluidflow.2024.109611>
9. Yang, X.L., Lü, Y.J., Xu, L., Ma, Y.S., Chen, R.B., Li, Q.A. (2025). Erosion wear and flow characteristics of the tri-eccentric butterfly valve in slurry flow. *Journal of Applied Fluid Mechanics*, Vol. 18 (11), pp. 2711–2729. <https://doi.org/10.47176/jafm.18.11.3564>
10. Munsch, P., Kiermeir, J., Schilling, R., Schlücker, E., Skoda, R. (2024). Three-dimensional simulation of cavitating flow in reciprocating positive displacement pumps with fluid-actuated valves. *Journal of Fluids Engineering*, Vol. 147(4), 041201. <https://doi.org/10.1115/1.4066751>
11. Qiu, N., Shang, X., Liu, R., Jin, P., Gao, W. (2022). Analysis of the dynamic characteristics of the pump valve system of an ultra-high pressure liquid hydrogen reciprocating pump. *Energies*, Vol. 15(12), 4255. <https://doi.org/10.3390/en15124255>
12. Wu, W., Yang, S., Ren, H., Xie, X. (2025). Valve disc dynamics of a reciprocating liquid hydrogen pump. *Cryo*, Vol. 1(1), 4. <https://doi.org/10.3390/cryo1010004>
13. Ge, T., Hu, L., Su, R., Ruan, X. (2023). Analysis of cavitation and shear in bellows pump: Transient CFD modelling and high-speed visualization. *Engineering Applications of Computational Fluid Mechanics*, Vol. 17(1), 2247474. <https://doi.org/10.1080/19942060.2023.2247474>
14. Singh, J., Kumar, S., Gill, H.S. (2024). Review on testing facilities assisting in development of numerical models for erosion calculation in centrifugal slurry pumps. *International Journal on Interactive Design and Manufacturing*, Vol. 18, pp. 5301–5327. <https://doi.org/10.1007/s12008-023-01282-z>
15. Korobko, B., Zadvorkin, D., Vasyliiev, I. (2017). Study of the operating element motion law for a hydraulic-driven diaphragm mortar pump. *Eastern-European Journal of Enterprise Technologies*, Vol. 4(7(88)), pp. 25–31. <https://doi.org/10.15587/1729-4061.2017.106873>
16. Li, R., Wei, W., Liu, H., Ye, J., Wang, D., Li, S., Wang, W. (2022). Experimental and numerical study on the dynamic and flow characteristics of a reciprocating pump valve. *Processes*, Vol. 10(7), 1328. <https://doi.org/10.3390/pr10071328>
17. Menéndez-Blanco, A., Oro, J.M.F., Meana-Fernández, A. (2019). Unsteady three-dimensional modeling of the fluid–structure interaction in the check valves of diaphragm volumetric pumps. *Journal of Fluids and Structures*, Vol. 90, pp. 432–449. <https://doi.org/10.1016/j.jfluidstructs.2019.07.008>
18. Żyłka, M., Marszałek, N., Żyłka, W. (2023). Numerical simulation of pneumatic throttle check valve using computational fluid dynamics (CFD). *Scientific Reports*, Vol. 13, 2475. <https://doi.org/10.1038/s41598-023-29457-4>
19. Cheng, Y., Tang, Y., Wu, J., Jin, H., Shen, L. (2024). Numerical simulation study on hydraulic characteristics and wear of eccentric semi-ball valve under sediment laden water flow. *Sustainability*, Vol. 16(17), 7266. <https://doi.org/10.3390/su16177266>
20. Wang, G., Zhong, L., He, X., Lei, Z., Hu, G., Li, R., Wang, Y. (2015). Dynamic behavior of reciprocating plunger pump discharge valve based on fluid structure interaction and experimental analysis. *Plos One*, Vol. 10(10), e0140396. <https://doi.org/10.1371/journal.pone.0140396>
21. Wang, Y., He, T., Ding, Q., Gao, P., Tao, R., Zhu, Z. (2022). Analysis of internal flow and wear characteristics of binary mixture particles in centrifugal pump based on CFD-DEM. *Processes*, Vol. 10(4), 681. <https://doi.org/10.3390/pr10040681>
22. Gu, Z., Bai, C., Zhang, H. (2023). Dynamic modeling of reciprocating pump valves with considering the interaction effects between pump and pipeline. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, Vol. 236(8), pp. 1491–1502. <https://doi.org/10.1177/09596518221098294>

23. Qiu, G., Zhu, S., Wang, K., Wang, W., Hu, J., Hu, Y., Zhi, X., Qiu, L. (2023). Numerical study on the dynamic process of reciprocating liquid hydrogen pumps for hydrogen refueling stations. *Energy*, 281, 128303. <https://doi.org/10.1016/j.energy.2023.128303>
24. Hu, G., Deng, S., Wang, G., Wang, M., Xie, M. (2022). Corrosion crack's propagation analysis and fatigue life prediction of the cylinder of 6000HP hydraulic fracturing pump. *Engineering Failure Analysis*, Vol. 141, 106652. <https://doi.org/10.1016/j.engfailanal.2022.106652>
25. Li, R., Wei, W., Lai, Y., Lu, H., Cao, T., Ye, J., Liu, H. (2025). Experimental and numerical study on valve dynamic impact characteristics and fault diagnosis of reciprocating piston pump valves. *Science Progress*, Vol. 108(1), pp. 1–20. <https://doi.org/10.1177/00368504251325327>
26. Gu, Z., Bai, C., Zhang, H. (2023). Experimental and numerical research on fluid dynamic interaction effects of reciprocating pump–pipeline system. *Journal of Pressure Vessel Technology*, Vol. 145 (3), 031401. <https://doi.org/10.1115/1.4057059>
27. Carpintero, J., Martinez, B., Fábregas, J., Pérez, J., Canales, F.A. (2023). Hydraulic characterization of a check valve for low-pressure potable water distribution applications. *Water*, 15 (13), 2475. <https://doi.org/10.3390/w15132475>