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Influence of needle geometry and stroke ratio on pressure distribution and hydraulic losses in a Pelton turbine injector

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Abstract. The Pelton injector plays a critical role in governing the overall energy conversion efficiency of Pelton turbines, as its geometric design and operating conditions directly influence jet formation, hydraulic losses, and component durability. In the present study, a numerical investigation is conducted to examine the effects of needle angle and stroke ratio on pressure distribution over the needle surface and head loss within the injector. The water–air interface is captured using the Volume of Fluid (VOF) method to accurately resolve free-surface jet dynamics. The results reveal that both needle geometry and stroke ratio significantly affect the hydraulic loading and shear characteristics of the needle. Increasing the needle angle and stroke ratio intensifies pressure loading on the needle, thereby enhancing the susceptibility of the needle tip to pressure-induced structural damage. In particular, the area-averaged needle pressure increases by approximately 22% when the needle angle is raised from 40° to 60°, indicating a substantial rise in mechanical loading. Furthermore, increasing the needle angle and stroke ratio results in a noticeable reduction in injector head loss, reflecting improved hydraulic efficiency due to reduced viscous dissipation. In contrast, lower needle angles and stroke ratios are associated with pronounced pressure reduction near the needle tip, indicating an elevated risk of cavitation inception under part-load operating conditions. Overall, this study highlights the importance of simultaneously optimizing needle design and operating stroke ratio to achieve a balanced compromise between hydraulic efficiency, cavitation mitigation, and structural integrity of the injector.

Keywords: Pelton injector, needle angle, stroke ratio, pressure distribution, head loss.

1 Introduction

Growing concerns over the environmental impacts of greenhouse gas emissions have accelerated the global transition toward sustainable energy sources. Projections indicate that by 2025, electricity generated from renewable resources will account for an additional 26.7% compared to 2020, with hydropower contributing the largest portion of this increase [1]. Among hydraulic turbines, Pelton turbines are predominantly employed in high-head applications exceeding 250 m, owing to their high efficiency and stable performance across a broad range of operating conditions. In Pelton turbines, power output is controlled by varying the discharge through axial movement of the needle, which alters the effective nozzle exit area [2-3]. Thus, the needle constitutes a critical component of the Pelton injector, as it governs the internal flow characteristics and directly influences the overall performance of the turbine [4-5].

The design of the Pelton turbine needle plays a significant role in governing the internal flow dynamics of the injector and the resulting jet quality [6]. Variations in needle geometry alter the pressure and velocity fields within the injector, leading to changes in the intensity of flow-induced phenomena such as hydro-abrasive erosion, cavitation, structural loading, and overall turbine efficiency [7]. Through numerical investigation, Zhang et al. [8] reported that an increase in needle angle can enhance injector efficiency. However, this behaviour cannot be universally generalized, as injector performance is also strongly affected by operating conditions, flow rate, and injector configuration, including the use of internal or external servomotors. Similarly, Benzon et al. [9] demonstrated that a nozzle/needle angle combination of 110°/70° reduced injector losses by approximately 0.5% when compared to a 90°/50° configuration. While higher needle angles may improve hydraulic performance, they can also intensify erosion-related effects. Shrivastava and Rai [10] showed that increasing the needle tip angle leads to enhanced erosion on the nozzle surface, whereas lower needle angles make the needle itself more vulnerable to erosive wear. This highlights the need for a balanced optimization approach in which both hydraulic losses and hydro-abrasive erosion are jointly evaluated to ensure reliable and efficient injector performance. Injector performance is closely associated with local flow conditions near the needle tip, where pressure tends to increase due to a velocity deficit caused by boundary layer development. As a result, the needle tip experiences elevated hydraulic forces, increasing its susceptibility to mechanical damage and failure. Furthermore, an increase in needle tip cut exacerbates hydraulic efficiency losses and promotes bubble formation in the downstream region, further degrading jet quality [11].

In addition to needle geometry, the axial position of the needle, which governs the flow rate, is a decisive parameter influencing injector losses and flow-induced phenomena. Zhang et al. [8] reported lower jet hydraulic losses at higher flow rates; however, losses associated with distributor bends and bifurcations tend to increase under high-flow conditions. Consequently, this trend cannot be generalized, as injector losses are strongly dependent on design characteristics such as nozzle pipe bend angle, injector configuration, and the number of injectors employed. At part-load operation, the needle becomes more susceptible to erosion and cavitation due to locally increased flow velocities and unfavourable pressure gradients. In this regard, Shrivastava et al.

[12] reported a substantial reduction in erosion intensity of approximately 78% as the stroke ratio increased from 0.35 to 0.8. Furthermore, jet quality degradation caused by needle eccentricity is more pronounced under part-load conditions, further aggravating hydraulic losses and flow instability.

Therefore, both needle geometry and stroke ratio are critical parameters that must be considered when analysing the flow characteristics of a Pelton injector and are accordingly examined in the present study. Despite their importance, detailed investigations focusing on the pressure distribution along the needle surface under varying needle angles and stroke ratios remain limited in the existing literature. Such an analysis is essential because the pressure distribution directly governs the hydraulic loading (mechanical stress) on the needle and is closely linked to the initiation of cavitation and the synergistic effects of hydro-abrasive erosion, particularly in high-head applications. A comprehensive understanding of these pressure variations is thus necessary to support improved injector design and reliable operation, thereby providing the primary motivation for the present investigation. In addition, the present study relates injector flow losses to needle wall shear stress under varying needle angles and stroke ratios, an aspect not addressed in earlier studies[8-9].

2 Methodology

The external servomotor Pelton injector configuration considered for the present analysis consists of a fixed nozzle pipe bend angle of 120°, a nozzle angle of 90°, and a nozzle exit diameter (D_O) of 100 mm, as shown in Fig. 1. For the parametric analysis, the needle angle and stroke ratio, defined as the ratio of needle stroke length (S) to the nozzle exit diameter, were varied. At the inlet, a pressure corresponding to a net head of 820 m, representative of the Kashang hydropower plant, was applied, while a zero-gauge pressure condition was imposed at the outlet.

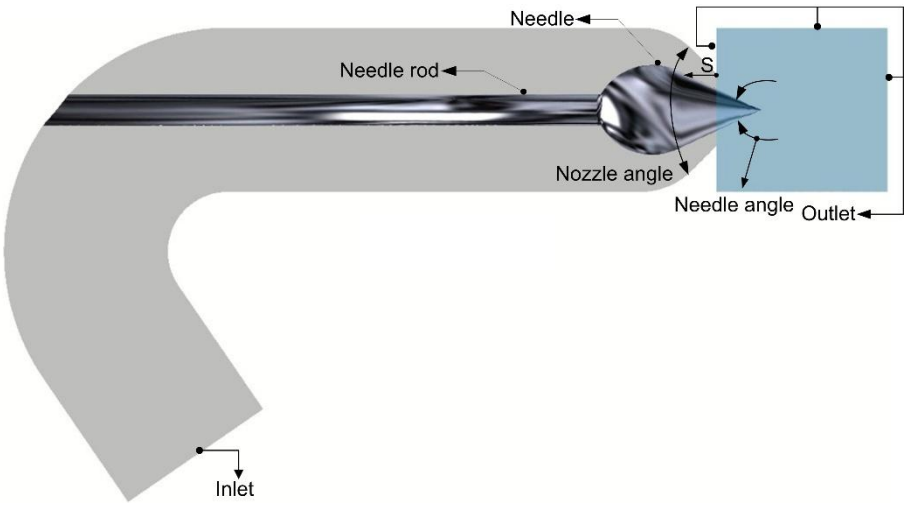


Fig. 1. Configuration of the computational domain of the Pelton injector considered for analysis.

A structured mesh was generated using Ansys Meshing to ensure numerical stability and faster convergence, as shown in Fig. 2. To verify that the obtained results were independent of the mesh density, a mesh independence study was performed. It was observed that variations in mass flow rate beyond 2.81 million mesh elements were negligible, as shown in Fig. 3 (a), and therefore this mesh density was selected for all simulations. A multiphase flow framework was employed using the Volume of Fluid (VOF) approach to capture the interaction between water and air and to accurately track their interface [10]. The governing continuity and momentum equations associated with this formulation are provided in eq. (1) and eq. (2). Interfacial properties within the VOF methodology are evaluated by accounting for the weighted contribution of each phase, as expressed in eq. (3), while the definition of the water phase volume fraction is given in eq. (4).

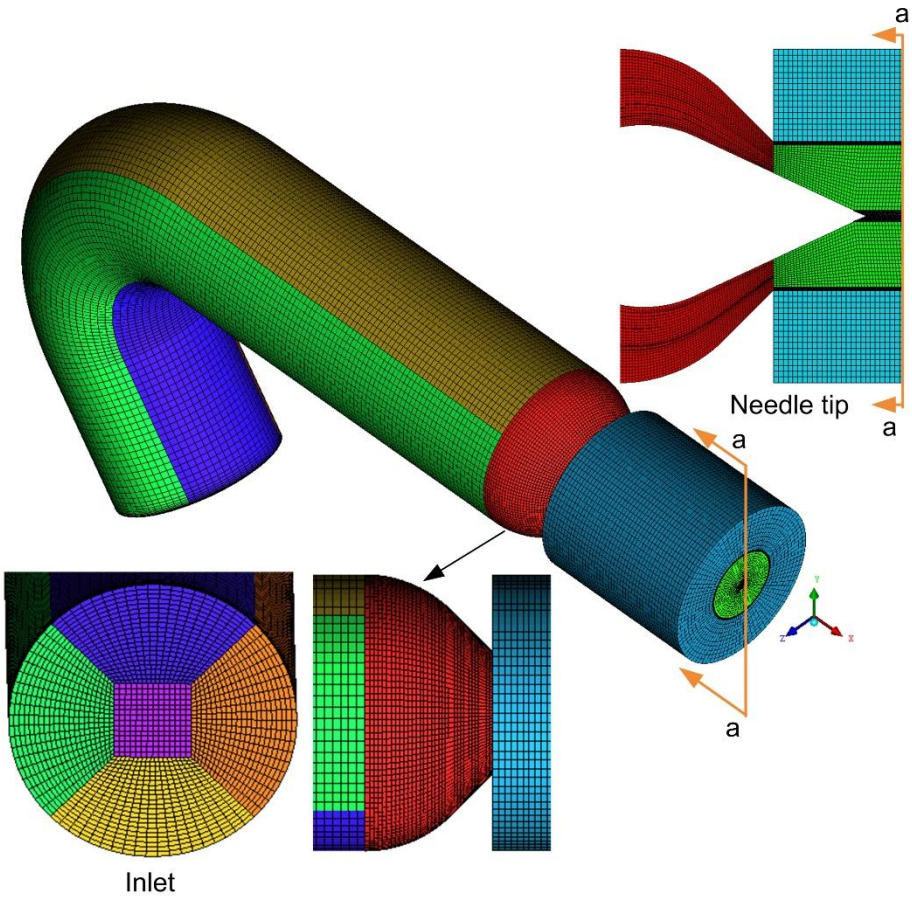


Fig. 2. Structured mesh of computational domain.

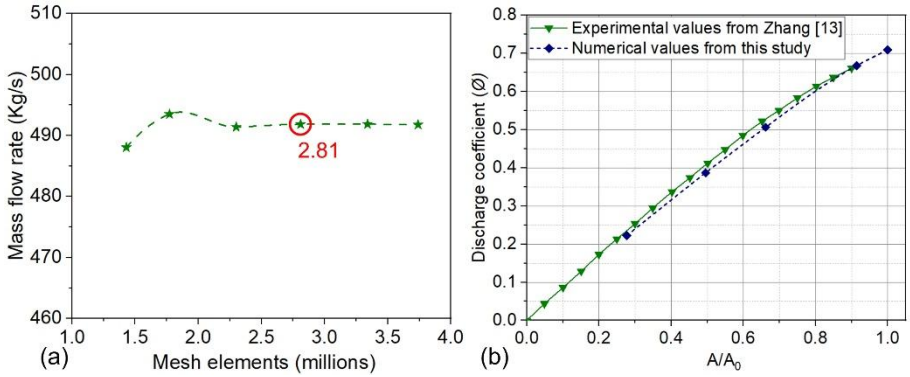


Fig. 3. (a) Mesh independence test (b) Validation of obtained values numerically [10].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{V}\right) \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho \vec{V}\right) + \nabla \cdot \left(\rho \vec{V}\,\vec{V}\right) = -\nabla p + \nabla \cdot \left[\mu\left(\nabla \vec{V} + \nabla \vec{V}^{T}\right)\right] + \rho \vec{g} \tag{2}$$

$$\beta = \beta_w \Phi_w + \beta_a \Phi_a \tag{3}$$

$$\Phi_w = 1 - \Phi_a \tag{4}$$

In these equations, ρ represents the fluid density, t denotes time, V is the velocity vector, p corresponds to pressure, μ indicates the dynamic viscosity, and g represents gravitational acceleration. The terms β_a and β_w denote the contributions of air and water, respectively, to the mixture property β, while Φ_a and Φ_w correspond to the volume fractions of air and water. The SST k–ω turbulence model was employed to represent turbulent flow behavior, as it provides reliable predictions in both near-wall and core flow regions by combining the advantages of the k–ω and k–ε formulations. Additionally, the coupled pressure–velocity algorithm was adopted to simultaneously solve the continuity and momentum equations, ensuring robust and efficient convergence. The validity of the numerical results was assessed through comparison with experimental data reported by Zhang [13]. The discharge coefficient, denoted by C_d and defined in eq. (5) was evaluated as a function of the ratio between the nozzle opening area at partial load (A) and that at full opening (A_o). The numerical predictions obtained in the present study show close agreement with the experimental measurements of Zhang (2016), as illustrated in Fig. 3 (b).

$$C_d = \frac{4Q}{\pi D_0^2 \sqrt{2gH}} \tag{5}$$

where, Q represents discharge (m^3/s), g represents the gravity (m^2/s), D_0 represents the exit diameter od nozzle (m), and H (m) represent the head considered. When analyzing the effect of needle angle (40°, 50°, and 60°) stroke ratio was kept constant at 0.45.

While analyzing the effect of stroke ratio (0.45, 0.75, 1.05) needle angle was kept constant at 50°.

3 Results and discussion

This section presents a detailed analysis of the effects of needle angle and stroke ratio on pressure distribution over the needle surface and the resulting injector head loss.

3.1 Effect of needle angle on pressure distribution and head loss

As the needle angle decreases, a larger portion of the needle surface becomes exposed to the high-velocity jet. This increases the effective area subjected to locally accelerated flow, resulting in an expanded low-pressure region on the needle surface (Fig. 4). Consequently, the area-averaged pressure acting on the needle decreases with decreasing needle angle (Fig. 5), while flow acceleration near the nozzle exit intensifies. This indicates that lower needle angles can exhibit higher cavitation susceptibility, in a region a little upstream of the needle tip, especially for an injector operating in erosive and ultra-high head conditions. From an actuation perspective, the reduced stagnation pressure surface associated with lower needle angles reduces the hydraulic assistance available during closing, thereby increasing the actuation force required to close the nozzle. Conversely, higher needle angles promote a larger stagnation pressure surface upstream of the needle, which increases resistance to opening. Within the investigated range, the 50° needle angle represents a balanced configuration, offering moderate stagnation pressure for controllability while limiting excessive low-pressure regions and actuation force asymmetry. It is also observed that the local pressure at the needle tip increases with increasing needle angle, leading to higher localized hydraulic loading. Thus, the susceptibility of the needle tip to structural damage at higher needle angles is greater.

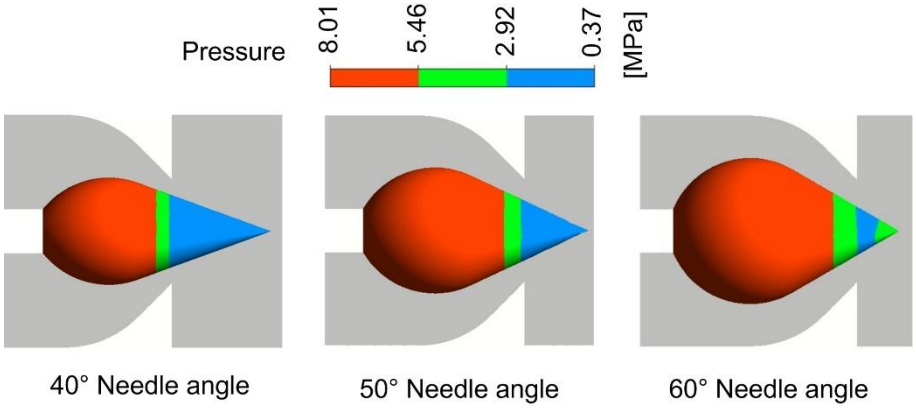


Fig. 4. Effect of needle angle on pressure distribution.

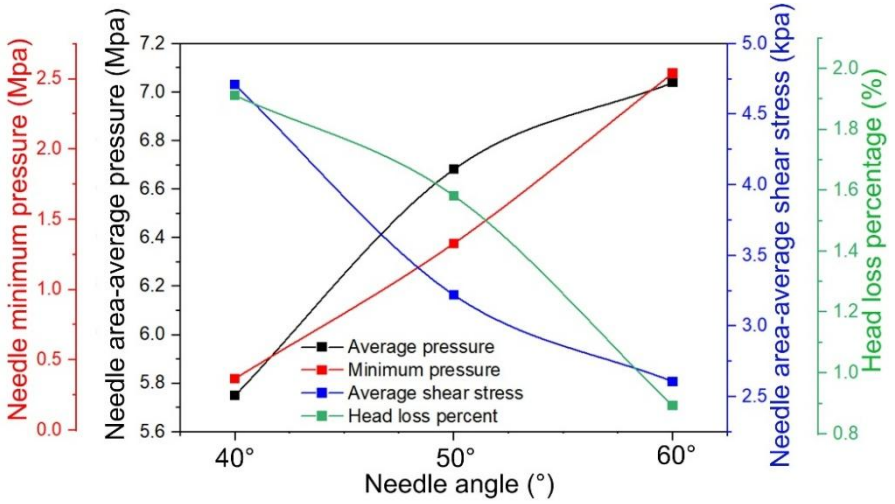


Fig. 5. Variation in different flow parameters with needle angle.

Regions of the needle surface exposed to the high-velocity jet experience strong velocity variation in the direction normal to the wall, leading to elevated wall shear stress [14]. At lower needle angles, a greater fraction of the needle surface is directly impinged by the jet, which enlarges the high-shear stress region (Fig. 6). This results in a higher area-averaged wall shear stress compared to larger needle angles. Since the stroke ratio is maintained constant for all needle configurations, the relative head loss, defined as the ratio of the total pressure drop between the injector inlet and a jet cross-section located at $2D_O$ downstream of the nozzle exit to the inlet total pressure, is primarily governed by variation in viscous dissipation with needle design. As the average wall shear stress on the needle surface increases with decreasing needle angle, the associated viscous losses intensify, resulting in a higher head loss for lower needle angles, as shown in Fig. 5 [15-16]. The observed dependence of head loss on needle angle is in good agreement with the findings of Benzon et al. [9], thereby confirming that needle angle is a key geometric parameter governing viscous losses and, consequently, the hydraulic efficiency of the injection system.

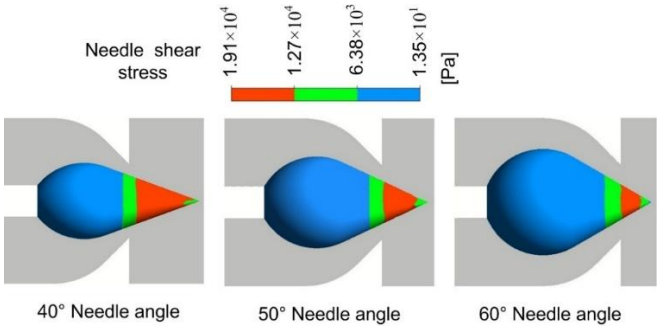


Fig. 6. Effect of needle angle on shear stress distribution.

3.2 Effect of stroke ratio on pressure distribution and head loss

The portion of the needle surface directly exposed to the jet is characterized by elevated flow velocities, which result in locally reduced static pressure due to flow acceleration. As the stroke ratio decreases, the extent of the needle surface interacting with the jet enlarges, thereby increasing the area subjected to high-velocity flow and low static pressure as shown in Fig. 7. Consequently, under part-load operating conditions (lower stroke ratios), the needle experiences a reduced area-averaged pressure due to the limited stagnation region and enhanced jet-induced acceleration (Fig. 8). Furthermore, the stronger local acceleration associated with part-load operation leads to a pronounced reduction in minimum pressure near the needle tip (Fig.7 and Fig. 8). This reduction in minimum pressure increases the susceptibility to cavitation, particularly for injectors operating under ultra-high head conditions and in sediment-laden environments, where cavitation–erosion interaction can significantly accelerate material degradation. It is also observed that the local pressure at the needle tip increases with increasing stroke ratio, leading to higher localized hydraulic loading. Thus, the susceptibility of the needle tip to structural damage at a higher stroke ratio is greater.

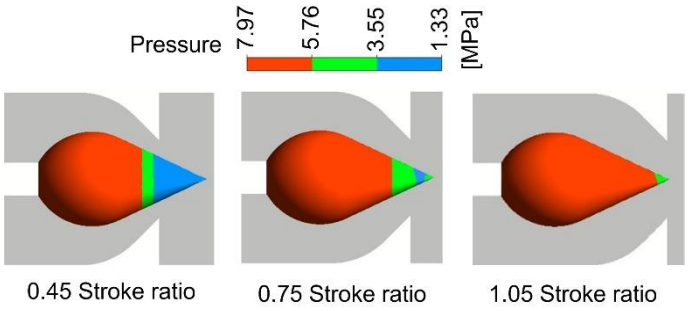


Fig. 7. Effect of stroke ratio on pressure distribution.

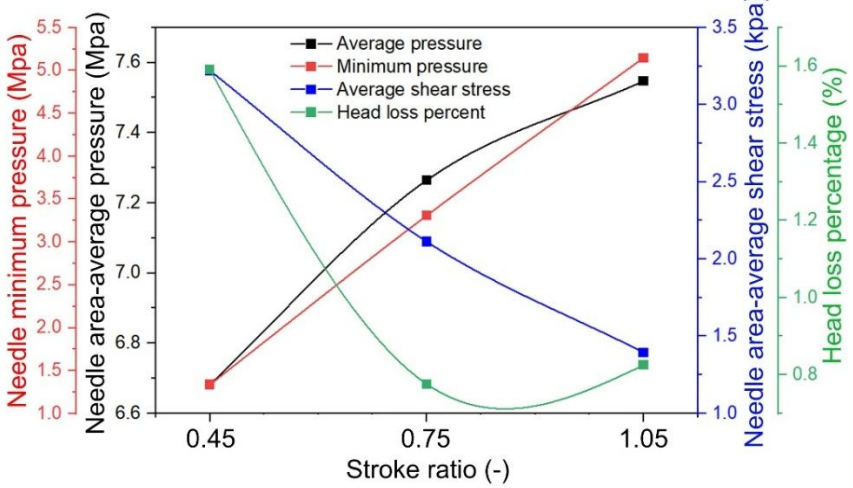


Fig. 8. Variation in different flow parameters with stroke ratio.

The average pressure acting on the conical region of the needle (towards the tip) varies significantly with stroke ratio, whereas the pressure on the upstream body of the needle (rear side) remains relatively insensitive to stroke variation. At lower stroke ratios, the needle is closer to the nozzle exit, and the flow undergoes strong acceleration near the tip, resulting in reduced pressure on the conical region. Consequently, the axial hydraulic force opposing needle closure is weakened, making needle closing hydraulically easier. As the stroke ratio increases, the conical region of the needle experiences higher pressure, generating a stronger axial hydraulic force acting in the upstream direction. This pressure-induced force assists needle opening. This interpretation is in agreement with the observations of Khan et al. [5], who demonstrated that variations in needle position significantly influence the hydraulic loading within the injector.

At lower stroke ratios, a larger fraction of the needle surface is directly exposed to the high-velocity jet, which intensifies velocity gradients normal to the needle wall and enlarges the high shear stress region as shown in Fig. 9. Consequently, the area-averaged wall shear stress increases as the stroke ratio decreases (Fig. 8). When the stroke ratio is varied, the relative head loss is governed by the combined effects of viscous dissipation along the needle surface and minor losses associated with mass flow rate variation within the nozzle passage. As the stroke ratio decreases from 1.05 to 0.75, the head loss exhibits a slight reduction, indicating that the decrease in mass-flow-dependent minor losses outweighs the corresponding increase in viscous dissipation. However, with further reduction in stroke ratio, from 0.75 to 0.45, the head loss increases markedly, suggesting that the rapid rise in viscous losses associated with elevated wall shear stress becomes the dominant dissipation mechanism (Fig. 8). This transition highlights the competing influence of flow rate–related losses and shear-induced viscous dissipation in determining the net head loss behavior. The observed reduction in the change in head loss with increasing stroke ratio is consistent with the findings reported by Benzon et al. [9], who demonstrated that injector losses become progressively less sensitive to needle displacement as the nozzle opening increases.

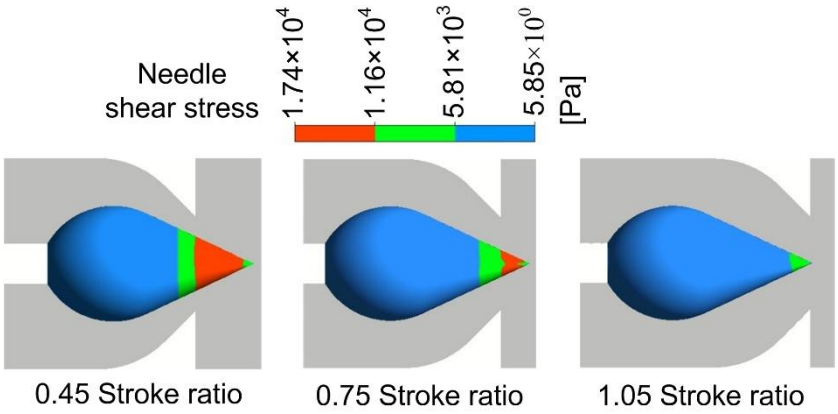


Fig. 9. Effect of stroke ratio on shear stress distribution.

4 Conclusion

In this study, numerical analysis is performed to analyze the effect of needle angle and stroke ratio on the pressure distribution of the needle and head loss in the Pelton injector. The major finding of the study is presented below.

- Pressure distribution in the needle is strongly governed by its geometry. As the needle angle decreases from 60° to 40°, the minimum pressure on the needle surface reduces by approximately 85%, indicating a significantly higher susceptibility to cavitation at lower needle angles. The 50° needle angle provides a favorable compromise between the hydraulic forces required for needle opening and closing. At both lower and higher needle angles, the disparity between opening and closing hydraulic forces becomes pronounced, potentially increasing control effort and mechanical loading on the actuation system.
- Needle angle also has a pronounced influence on shear-induced losses. As the needle angle increases from 40° to 60°, the area-averaged wall shear stress on the needle decreases by approximately 45%, accompanied by a 54% reduction in head loss. Under conditions of constant stroke ratio, these results indicate that needles with larger tip angles experience lower viscous dissipation, leading to improved hydraulic efficiency and reduced energy losses in the injector.
- Needle pressure is strongly influenced by the operating (loading) condition. As the stroke ratio decreases from 1.05 to 0.45, the minimum pressure on the needle surface reduces by approximately 74%, indicating a substantially increased susceptibility to cavitation under low-load operation. With increasing stroke ratio from 0.45 to 1.05, the pressure acting on the upstream (rear) portion of the needle changes marginally by only 1.6%, whereas the pressure on the conical region near the tip increases by approximately 44%. This disparity demonstrates that variations in hydraulic loading and hence actuation resistance during needle motion are governed predominantly by the pressure distribution on the conical region rather than the upstream needle body.
- The injector head loss exhibits a clear dependence on stroke ratio. The highest head loss occurs at the lowest stroke ratio (SR = 0.45), while increasing the stroke ratio leads to a progressive reduction in head loss. However, the rate of decrease in head loss diminishes at higher stroke ratios, indicating a reduced sensitivity of hydraulic losses to needle displacement as the injector approaches fully open conditions.

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