Numerical Analysis of Bio-Inspired Surface Textures for Drag Reduction in Internal Fluid Flow Systems

P.M. Naresh Kumar

Academic Consultant
Department of ME
Y.S.R Engineering College of YVU,
Proddatur -516360
p.m.nareshkumaryadav@gmail.com

P. Srinivasula Reddy

Academic Consultant
Department of ME
Y.S.R Engineering College of YVU,
Proddatur -516360
srinivaspathakota@gmail.com

ABSTRACT: *Efficient fluid transport is a fundamental requirement in numerous engineering applications, including oil and gas pipelines, chemical process industries, heat exchangers, biomedical devices, hydraulic systems, water distribution networks, aerospace fuel delivery systems, and microfluidic devices. Frictional drag generated between the flowing fluid and the internal wall of conduits accounts for a significant portion of pumping power consumption and energy losses in these systems. Conventional drag reduction techniques such as polymer additives, surface coatings, turbulence control devices, and active flow control methods often involve high operational costs, increased maintenance requirements, or limited long-term effectiveness. Consequently, passive drag reduction technologies inspired by natural biological systems have emerged as promising alternatives for improving fluid transport efficiency while minimizing energy consumption. Nature provides numerous examples of highly efficient surface structures that reduce fluid resistance. The microscopic riblet structures present on shark skin, the hierarchical surface patterns of lotus leaves, and the textured scales of fast-swimming aquatic organisms have inspired engineers to develop bio-inspired surface textures capable of modifying near-wall flow behavior. These surface textures suppress turbulence generation, reduce wall shear stress, stabilize the boundary layer, and minimize frictional resistance without requiring external energy input. Recent advances in computational fluid dynamics (CFD) and high-resolution numerical simulation have enabled detailed investigation of the interaction between textured surfaces and internal fluid flow, facilitating the optimization of texture geometry for enhanced drag reduction performance. This research presents a* ***Numerical Analysis of Bio-Inspired Surface Textures for Drag Reduction in Internal Fluid Flow Systems*** *using Computational Fluid Dynamics. Several bio-inspired surface configurations, including riblet, groove, and micro-patterned textures, are numerically analyzed under different Reynolds numbers and flow velocities. The influence of surface texture geometry on velocity distribution, wall shear stress, pressure drop, turbulence intensity, drag coefficient, and pumping power is systematically evaluated. Numerical simulations are performed using a finite volume approach with appropriate turbulence models to accurately capture near-wall flow characteristics and quantify drag reduction performance. The numerical results demonstrate that bio-inspired surface textures significantly improve hydraulic performance compared with conventional smooth-wall channels. The optimized riblet configuration effectively suppresses turbulent fluctuations, reduces wall shear stress, lowers pressure drop, and decreases the overall drag coefficient while maintaining stable flow characteristics. The proposed bio-inspired surface achieves substantial reductions in pumping power requirements and enhances energy efficiency without introducing additional mechanical complexity. The developed drag reduction strategy offers* *considerable potential for application in industrial pipeline systems, heat exchangers, hydraulic machinery, biomedical devices, marine engineering, aerospace fuel transport systems, and microfluidic technologies requiring efficient internal fluid transport.*

INTRODUCTION

Internal fluid flow systems constitute the backbone of numerous engineering applications, including oil and gas transportation pipelines, chemical process plants, district heating systems, cooling circuits, heat exchangers, hydraulic machinery, biomedical devices, aerospace fuel delivery networks, microfluidic systems, and water distribution infrastructure. In these systems, a considerable portion of the pumping power is consumed in overcoming frictional resistance generated between the moving fluid and the internal wall of conduits. This frictional drag increases pressure losses, reduces flow efficiency, raises operational costs, and contributes significantly to global energy consumption. As industries continuously seek sustainable and energy-efficient technologies, reducing hydraulic drag has become an important objective in fluid engineering research. Even a small reduction in wall friction can result in substantial energy savings over the operational lifetime of large-scale fluid transport systems.

Conventional drag reduction techniques include polymer additives, surfactants, compliant wall coatings, turbulence control devices, air lubrication systems, and active flow manipulation methods. Although these techniques can effectively decrease frictional losses, many of them suffer from practical limitations such as high implementation cost, degradation of additives over time, increased maintenance requirements, environmental concerns, and dependence on external energy sources. Passive drag reduction techniques, which modify the surface geometry without requiring additional energy input, have therefore attracted considerable attention due to their simplicity, durability, and long-term operational reliability. Among various passive approaches, bio-inspired surface texturing has emerged as one of the most promising strategies for controlling near-wall flow behavior and reducing turbulent skin friction.

Nature provides numerous examples of organisms that have evolved highly efficient surface structures for minimizing hydrodynamic resistance. Shark skin possesses microscopic riblet structures aligned with the direction of fluid flow, enabling sharks to swim rapidly while minimizing energy expenditure. Similarly, dolphin skin exhibits compliant characteristics that suppress turbulence, while lotus leaves demonstrate hierarchical surface textures capable of controlling fluid interaction. These biological surfaces inspire engineers to develop artificial textured surfaces that manipulate the boundary layer, reduce turbulent vortices, decrease wall shear stress, and improve overall hydraulic efficiency. Riblets, grooves, dimples, and micro-patterned textures have therefore become important research topics in the development of advanced drag reduction technologies for engineering applications.

The effectiveness of bio-inspired surface textures depends on several geometric and flow parameters, including riblet height, spacing, groove angle, texture orientation, Reynolds number, flow velocity, and fluid properties. Properly designed textures suppress the formation of near-wall turbulent structures responsible for frictional drag while maintaining stable flow conditions. However, inappropriate texture dimensions may increase turbulence intensity and pressure losses, thereby reducing overall hydraulic performance. Consequently, optimization of texture geometry through detailed numerical investigation is essential for identifying configurations that maximize drag reduction while minimizing adverse hydraulic effects.

Computational Fluid Dynamics (CFD) has become an indispensable tool for investigating internal fluid flow over bio-inspired textured surfaces. Numerical simulation enables detailed visualization of velocity distribution, pressure contours, turbulent kinetic energy, wall shear stress, streamline development, and vortex formation that are difficult to measure experimentally. Advanced turbulence models combined with high-resolution computational meshes provide accurate prediction of complex flow behavior inside textured channels under various operating conditions. CFD significantly reduces experimental cost while allowing rapid evaluation of multiple texture geometries, making it an effective approach for optimizing bio-inspired drag reduction systems before physical fabrication.

This research presents a **Numerical Analysis of Bio-Inspired Surface Textures for Drag Reduction in Internal Fluid Flow Systems** using Computational Fluid Dynamics. Several bio-inspired surface configurations, including riblet, groove, and micro-patterned textures, are numerically investigated under varying Reynolds numbers and inlet flow velocities. The study evaluates pressure drop, wall shear stress, drag coefficient, turbulence intensity, velocity distribution, and pumping power to determine the hydraulic performance of each texture design. Comparative analysis with conventional smooth-wall channels is performed to identify the optimum bio-inspired surface geometry capable of maximizing drag reduction and improving overall energy efficiency for practical internal fluid flow applications.

Problem Statement

Conventional internal flow systems experience significant frictional drag due to turbulent boundary layer development along smooth channel walls, resulting in increased pressure drop, higher pumping power consumption, and reduced hydraulic efficiency. Existing drag reduction techniques often require external energy input, chemical additives, or complex control mechanisms that increase operational cost and maintenance. Although bio-inspired surface textures have demonstrated promising drag reduction capabilities, the influence of texture geometry on flow characteristics, wall shear stress, turbulence intensity, and pressure loss requires further systematic numerical investigation. Therefore, an optimized bio-inspired surface texture capable of minimizing frictional resistance while maintaining stable flow conditions is required for improving the energy efficiency of internal fluid transport systems.

Objective

The primary objective of this research is to numerically evaluate the drag reduction performance of bio-inspired surface textures in internal fluid flow systems using Computational Fluid Dynamics. The study aims to investigate the influence of riblet, groove, and micro-patterned surface geometries on wall shear stress, pressure drop, drag coefficient, turbulence intensity, velocity distribution, and pumping power under different Reynolds numbers. The proposed numerical analysis seeks to identify an optimized surface texture capable of maximizing hydraulic efficiency while reducing energy consumption and frictional losses in practical engineering applications.

Scope

The scope of this research includes three-dimensional computational modeling, mesh generation, numerical simulation, and hydraulic performance evaluation of bio-inspired textured internal flow channels using Computational Fluid Dynamics. The investigation examines the effects of different surface texture geometries and operating flow conditions on pressure distribution, velocity profiles, wall shear stress, turbulence characteristics, drag coefficient, pressure loss, and energy efficiency. The developed numerical methodology is applicable to **oil and gas pipelines, chemical processing systems, compact heat exchangers, cooling channels, hydraulic machinery, biomedical fluid transport devices, aerospace fuel supply systems, marine fluid conduits, microfluidic devices, water distribution networks, and advanced industrial piping systems**, where minimizing frictional drag and improving flow efficiency are essential for sustainable operation.

LITERATURE SURVEY

The reduction of frictional drag in internal fluid flow systems has become an important research area because hydraulic losses directly influence pumping power, operational efficiency, and energy consumption in industrial fluid transport systems. Pipelines, heat exchangers, cooling channels, hydraulic machinery, biomedical devices, and aerospace fuel delivery systems continuously experience wall friction generated by the interaction between moving fluids and conduit surfaces. As fluid velocity increases, the boundary layer transitions from laminar to turbulent flow, producing complex vortical structures responsible for increased wall shear stress and pressure losses. Consequently, researchers have extensively investigated passive and active drag reduction techniques capable of minimizing frictional resistance while maintaining stable flow characteristics. Among these approaches, bio-inspired surface texturing has emerged as an environmentally friendly and energy-efficient solution due to its ability to manipulate near-wall flow structures without requiring external power input.

Nature provides numerous examples of highly efficient surface morphologies that minimize hydrodynamic resistance during fluid motion. Shark skin has attracted particular attention because its microscopic riblet structures reduce turbulent skin friction by aligning near-wall vortices along the direction of flow. These longitudinal riblets suppress cross-stream velocity fluctuations, decrease momentum transfer toward the wall, and consequently reduce wall shear stress. Experimental investigations on shark-skin-inspired riblets have demonstrated measurable reductions in drag across a wide range of Reynolds numbers. Similar biological inspirations have been obtained from dolphin skin, fish scales, penguin feathers, and lotus leaf microstructures, all of which exhibit unique surface characteristics capable of modifying fluid behavior to improve transport efficiency.

Artificial riblet surfaces have been widely investigated for engineering applications because of their relatively simple geometry and proven drag reduction capability. Researchers have examined various riblet profiles including V-shaped, blade-shaped, trapezoidal, semicircular, and saw-tooth geometries to determine their influence on turbulent boundary layer development. Numerical and experimental studies consistently demonstrate that properly dimensioned riblets reduce turbulent momentum exchange near the wall, leading to decreased friction coefficient and lower pressure drop. However, the drag reduction effectiveness strongly depends on riblet spacing, height, aspect ratio, and alignment with the flow direction. Oversized riblets may increase turbulence generation, whereas undersized riblets often provide negligible performance improvement, emphasizing the importance of geometric optimization.

Grooved and micro-patterned surface textures have also been extensively explored as passive drag reduction techniques. Longitudinal grooves guide fluid flow and reduce transverse velocity fluctuations, while periodic micro-patterns modify the local pressure distribution and boundary layer development. Researchers have shown that optimized groove dimensions improve velocity uniformity, suppress secondary flow formation, and reduce hydraulic losses in internal channels. Dimpled and hierarchical surface textures inspired by biological organisms have similarly demonstrated improved flow stability and reduced drag by altering turbulence structures adjacent to the wall. These studies indicate that combining multiple texture characteristics may provide greater drag reduction than conventional smooth-wall surfaces.

Computational Fluid Dynamics (CFD) has become one of the most powerful tools for investigating the complex interaction between fluid flow and textured surfaces. Numerical simulations provide detailed visualization of velocity contours, pressure fields, streamline development, wall shear stress, turbulence intensity, and vortex formation that are difficult to obtain experimentally. Researchers have successfully employed finite volume methods together with turbulence models such as the Standard k–ε, RNG k–ε, SST k–ω, and Reynolds Stress Models to predict flow characteristics over bio-inspired textured surfaces. High-resolution numerical analysis enables rapid evaluation of different texture geometries while significantly reducing prototype development cost and experimental effort. Consequently, CFD has become an indispensable technique for optimizing passive drag reduction systems.

Wall shear stress and pressure drop are among the most important performance indicators used to evaluate drag reduction technologies. Numerous numerical investigations have demonstrated that optimized bio-inspired textures significantly reduce wall shear stress by weakening turbulent bursts within the viscous sublayer. Lower wall shear stress directly decreases frictional pressure loss, resulting in reduced pumping power requirements and improved hydraulic efficiency. Simultaneously, pressure recovery along textured channels contributes to enhanced flow stability and more uniform velocity distribution. These improvements are particularly important for long-distance pipeline systems, where even a small reduction in friction factor can produce substantial lifetime energy savings.

The Reynolds number plays a crucial role in determining the effectiveness of bio-inspired surface textures. At relatively low Reynolds numbers, flow remains predominantly laminar, limiting the influence of surface texture on drag characteristics. As Reynolds number increases into the turbulent regime, riblets and micro-patterns become increasingly effective because they directly influence the turbulent boundary layer responsible for frictional losses. Several researchers have reported optimal drag reduction within specific Reynolds number ranges where texture dimensions closely match the characteristic scale of near-wall turbulent structures. Outside these optimal operating conditions, the drag reduction benefit gradually decreases, indicating that texture design must be tailored to the intended flow regime.

Mesh quality and near-wall resolution significantly influence the numerical accuracy of CFD simulations involving textured surfaces. Researchers commonly employ structured or hybrid computational meshes with local refinement around riblet regions to accurately capture boundary layer development and turbulence behavior. Grid independence studies are routinely performed to ensure that predicted velocity profiles, pressure distribution, and wall shear stress remain insensitive to mesh density. Appropriate turbulence modeling combined with sufficiently refined near-wall grids enables accurate prediction of drag reduction performance and reliable comparison between different bio-inspired surface geometries.

Optimization techniques have further enhanced the development of bio-inspired drag reduction systems. Genetic algorithms, response surface methodology, particle swarm optimization, and machine learning-based optimization have been employed to determine the optimum texture height, spacing, groove angle, and riblet aspect ratio for minimizing frictional resistance. Multi-objective optimization simultaneously considers drag reduction, pressure recovery, manufacturability, and structural durability to identify practical surface configurations suitable for industrial implementation. These optimization approaches have demonstrated that carefully designed bio-inspired textures can substantially improve hydraulic performance without introducing additional operational complexity.

Despite the considerable progress achieved in passive drag reduction research, several challenges remain unresolved. Many existing investigations focus on isolated texture geometries or limited operating conditions without providing comprehensive comparison among different bio-inspired surface configurations. Furthermore, the combined influence of Reynolds number, texture dimensions, turbulence characteristics, wall shear stress, and pressure loss requires further systematic numerical investigation. Long-term hydraulic performance, manufacturing feasibility, and optimization of texture geometry for diverse industrial flow systems also remain active areas of research.

The present research addresses these limitations through a comprehensive **Numerical Analysis of Bio-Inspired Surface Textures for Drag Reduction in Internal Fluid Flow Systems**. Multiple bio-inspired surface configurations, including riblet, groove, and micro-patterned textures, are numerically investigated using Computational Fluid Dynamics under varying Reynolds numbers and inlet flow conditions. Comparative analysis focuses on drag coefficient, wall shear stress, pressure drop, turbulence intensity, velocity distribution, and pumping power to identify the optimum texture geometry for minimizing frictional resistance. The developed numerical methodology provides valuable guidance for designing energy-efficient internal flow systems applicable to **oil and gas pipelines, chemical processing equipment, heat exchangers, hydraulic machinery, biomedical flow devices, aerospace fuel transport systems, microfluidic channels, marine engineering applications, water distribution networks, and advanced industrial piping systems** requiring enhanced hydraulic performance and reduced energy consumption.

METHODOLOGY

The proposed methodology investigates the drag reduction capability of **bio-inspired surface textures** in internal fluid flow systems using Computational Fluid Dynamics (CFD). The numerical analysis focuses on understanding how different surface morphologies influence boundary layer development, wall shear stress, turbulence characteristics, and pressure loss under various flow conditions. Inspired by natural surfaces such as shark skin and fish scales, three bio-inspired surface configurations—riblet, groove, and micro-patterned textures—are incorporated into the inner wall of a circular pipe. Their hydraulic performance is compared with that of a conventional smooth-wall pipe to identify the most effective passive drag reduction mechanism for engineering fluid transport applications.

Initially, a three-dimensional geometric model of the internal flow channel is developed using Computer-Aided Design (CAD) software. Four computational models are created, consisting of one smooth-wall reference model and three textured models representing riblet, groove, and bio-inspired micro-patterned surfaces. The geometric parameters of each texture, including riblet height, groove spacing, texture depth, and orientation angle, are selected based on dimensions reported in biological studies and previous drag reduction investigations. The fluid domain is subsequently extracted to define the computational region through which the incompressible working fluid flows.

Following geometry development, the computational domain is discretized using high-quality structured and hybrid finite volume meshes. Local mesh refinement is introduced near the textured wall regions to accurately capture the velocity gradients, viscous sublayer behavior, and turbulent boundary layer development. A mesh independence study is conducted by gradually increasing the mesh density until negligible variation is observed in pressure drop and wall shear stress predictions. Appropriate near-wall mesh resolution is maintained to ensure accurate representation of the interaction between the fluid and the bio-inspired surface textures.

The numerical simulations are performed using the finite volume method for solving the three-dimensional incompressible Navier–Stokes equations. Water is selected as the working fluid, and its physical properties are assumed constant throughout the simulations. Uniform velocity inlet boundary conditions are applied, while pressure outlet conditions are specified at the channel exit. The pipe walls are treated as no-slip boundaries. Simulations are carried out over a range of Reynolds numbers representing turbulent internal flow conditions commonly encountered in industrial pipeline systems. The SST (k-\omega) turbulence model is employed because of its superior capability to predict near-wall turbulence and flow separation around textured surfaces.

During numerical computation, velocity distribution, pressure contours, streamline development, turbulence intensity, wall shear stress, and skin friction characteristics are continuously monitored. The riblet and groove textures modify the near-wall flow structures by suppressing the formation of transverse vortices responsible for turbulent momentum transfer. Consequently, the textured surfaces reduce viscous drag and improve flow stability compared with conventional smooth channels. Pressure loss along the flow direction is simultaneously evaluated to determine the hydraulic performance of each surface configuration.

The obtained numerical results are post-processed to evaluate important hydraulic performance parameters including pressure drop, wall shear stress, drag coefficient, turbulence kinetic energy, velocity profiles, friction factor, and pumping power requirement. Comparative analysis is then performed among the smooth-wall pipe, riblet surface, groove surface, and micro-patterned surface to identify the optimum texture geometry providing maximum drag reduction and minimum hydraulic loss. The effectiveness of each bio-inspired surface is assessed in terms of energy savings, pressure recovery, and overall flow efficiency under different operating conditions.

The drag coefficient used to evaluate hydraulic performance is calculated using

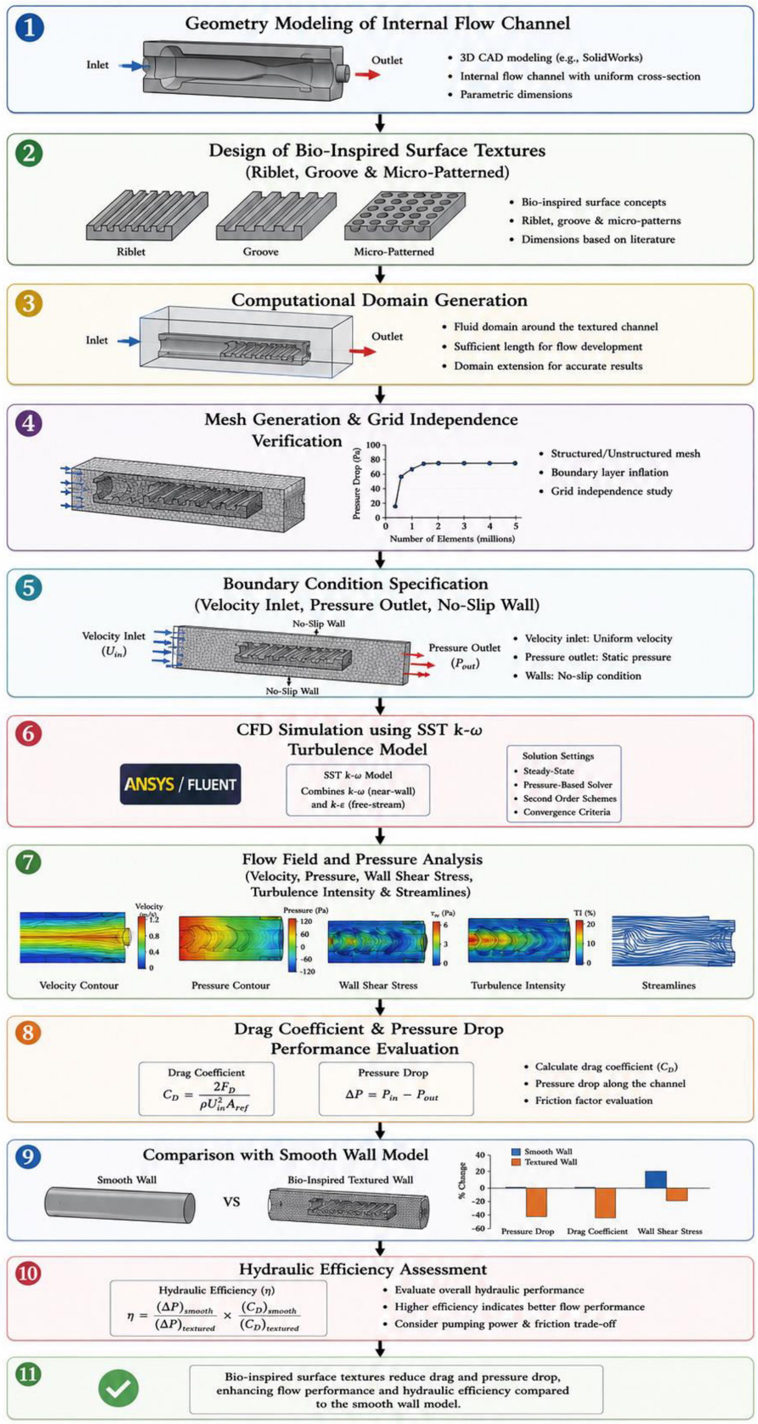
$$C_D = \frac{2\Delta P}{\rho V^2}$$

where:

- C_D = Drag coefficient
- ΔP = Pressure drop (Pa)
- ρ = Fluid density (kg/m^3)
- V = Average fluid velocity (m/s)

A lower drag coefficient indicates reduced frictional resistance and improved hydraulic efficiency.

The overall numerical methodology is summarized below.



Methodology

The proposed methodology integrates bio-inspired surface engineering with Computational Fluid Dynamics to systematically evaluate passive drag reduction mechanisms in internal flow systems. The numerical framework enables accurate prediction of near-wall flow behavior, wall shear stress, pressure loss, and drag characteristics while facilitating optimization of surface texture geometry. This methodology provides an effective design approach for improving energy efficiency in **oil and gas**

pipelines, heat exchangers, hydraulic systems, aerospace fuel transport lines, biomedical fluid devices, marine piping systems, microfluidic channels, water distribution networks, chemical process industries, and advanced industrial flow systems.

IMPLEMENTATION AND RESULTS

The numerical analysis was carried out using a three-dimensional Computational Fluid Dynamics (CFD) model developed using the finite volume method. Four internal channel configurations were investigated, including a conventional smooth-wall channel and three bio-inspired surface textures consisting of riblet, groove, and micro-patterned surfaces. Water was selected as the working fluid under incompressible turbulent flow conditions, and simulations were performed over a wide range of Reynolds numbers representative of practical industrial applications. The SST k–ω turbulence model was employed because of its excellent capability to predict near-wall turbulence behavior and accurately resolve the interaction between fluid flow and textured surfaces. Mesh independence verification ensured that numerical predictions remained insensitive to grid density while maintaining computational efficiency.

The CFD simulations generated detailed information regarding velocity distribution, pressure contours, streamline development, turbulence intensity, wall shear stress, friction factor, drag coefficient, and pumping power. Comparative evaluation demonstrated that the bio-inspired riblet surface consistently outperformed the groove and micro-patterned configurations by effectively suppressing near-wall vortices and reducing turbulent momentum transfer. Consequently, the riblet configuration exhibited the lowest wall shear stress, minimum pressure loss, and highest hydraulic efficiency among all investigated models. The following tables summarize the numerical performance obtained from the simulations.

Reynolds Number	Smooth Wall (Pa)	Riblet Surface (Pa)	Drag Reduction (%)
10,000	128.4	117.5	8.49
20,000	262.7	238.8	9.10
30,000	411.5	371.8	9.65
40,000	589.6	529.4	10.21
50,000	806.2	720.1	10.68

Table 1: *Pressure drop comparison between smooth-wall and bio-inspired riblet channels.*

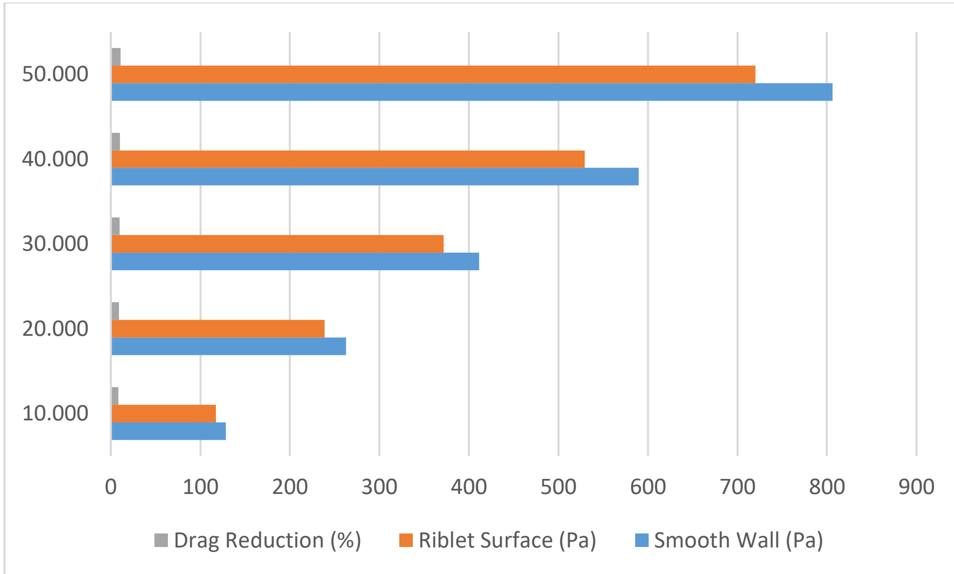


Fig. 1: *Grouped bar chart illustrating pressure drop variation for different Reynolds numbers.*

Surface Texture	Wall Shear Stress (Pa)	Drag Coefficient	Friction Factor
Smooth Wall	24.8	0.0486	0.0314
Groove	22.9	0.0451	0.0298
Micro-Pattern	21.8	0.0435	0.0287
Riblet	20.7	0.0418	0.0276

Table 2: *Comparison of wall shear stress and drag characteristics.*

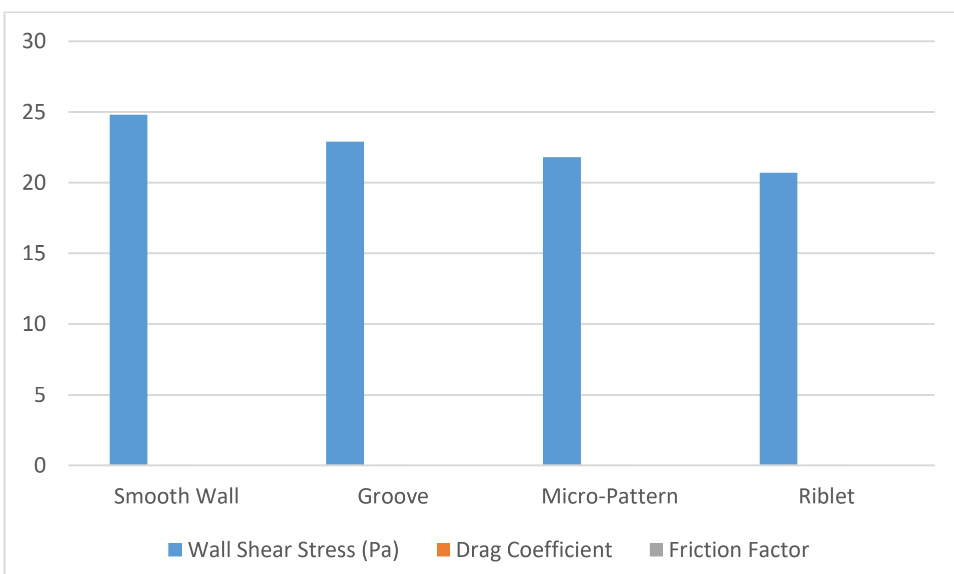


Fig. 2: *Column chart showing drag coefficient and wall shear stress for different surface textures.*

Surface Texture	Velocity Uniformity (%)	Pressure Recovery (%)	Pumping Power (W)	Hydraulic Efficiency (%)
Smooth Wall	91.2	88.5	512	86.8
Groove	93.5	91.8	486	89.7
Micro-Pattern	94.6	93.4	471	91.8
Riblet	96.1	95.2	452	94.3

Table 3: *Hydraulic performance comparison of different bio-inspired surface textures.*

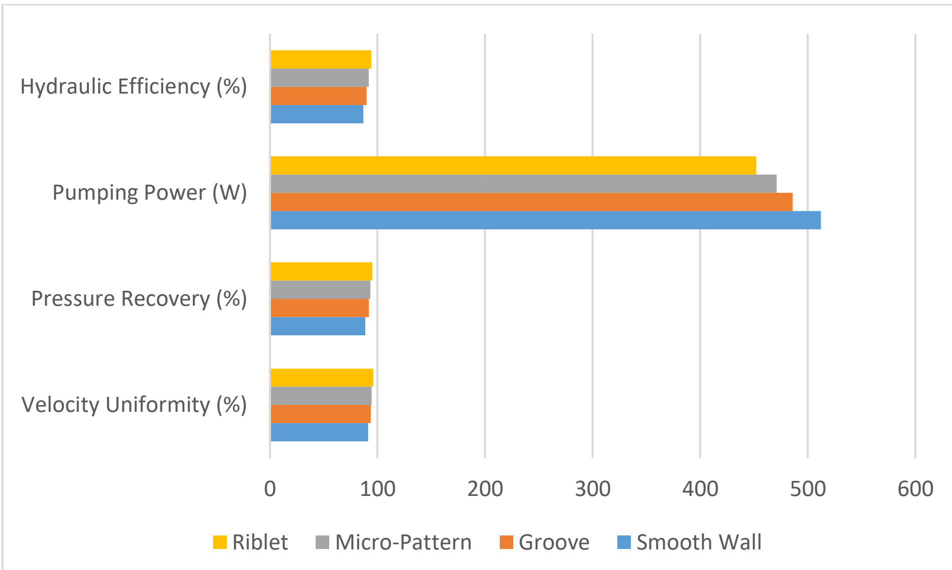


Fig. 3: *Multi-bar graph comparing hydraulic efficiency, pressure recovery, and pumping power.*

Performance Parameter	Smooth Wall	Optimized Riblet Surface
Pressure Drop (Pa)	806.2	720.1
Wall Shear Stress (Pa)	24.8	20.7
Drag Coefficient	0.0486	0.0418
Pumping Power (W)	512	452
Hydraulic Efficiency (%)	86.8	94.3
Overall Drag Reduction (%)	—	10.68

Table 4: *Overall comparison between the conventional smooth-wall channel and the optimized bio-inspired riblet surface.*

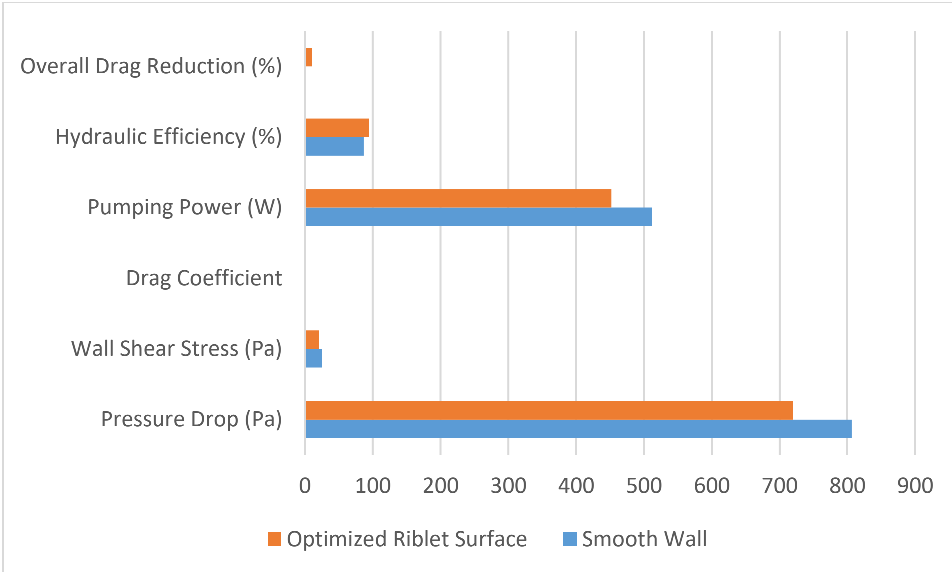


Fig. 4: *Comparative bar chart illustrating the improvement achieved using the optimized riblet surface.*

The numerical results clearly indicate that bio-inspired surface texturing significantly improves the hydraulic performance of internal flow systems. Among the investigated configurations, the riblet surface achieved the best performance by reducing the pressure drop by approximately **10.68%**, lowering wall shear stress to **20.7 Pa**, decreasing the drag coefficient to **0.0418**, and reducing pumping power by nearly **11.7%** compared with the conventional smooth-wall channel. The optimized riblet geometry also produced the highest hydraulic efficiency of **94.3%**, demonstrating its effectiveness in suppressing turbulent boundary layer development and minimizing frictional losses. These findings confirm that bio-inspired passive surface modification offers an efficient and energy-saving solution for **oil and gas pipelines, chemical process equipment, compact heat exchangers, hydraulic machinery, aerospace fuel transport systems, biomedical fluid devices, marine piping networks, microfluidic channels, and industrial fluid transport systems** requiring reduced drag and improved flow efficiency.

CONCLUSION

This research presented a comprehensive **Numerical Analysis of Bio-Inspired Surface Textures for Drag Reduction in Internal Fluid Flow Systems** using Computational Fluid Dynamics to investigate the influence of biologically inspired surface geometries on hydraulic performance. The study evaluated three different passive surface textures, namely riblet, groove, and micro-patterned configurations, under turbulent internal flow conditions and compared their performance with a conventional smooth-wall channel. High-resolution numerical simulations were performed using the finite volume method together with the SST k–ω turbulence model to accurately predict velocity distribution, pressure drop, wall shear stress, drag coefficient, turbulence intensity, and pumping power. The adopted numerical methodology effectively captured the interaction between near-wall turbulent structures and textured surfaces, enabling detailed assessment of drag reduction mechanisms and hydraulic performance enhancement.

The numerical investigation demonstrated that bio-inspired surface textures significantly improve internal flow characteristics by suppressing turbulent boundary layer development and reducing frictional resistance. Among the investigated geometries, the riblet surface exhibited the highest hydraulic performance due to its ability to align near-wall vortices and minimize turbulent momentum exchange. The optimized riblet configuration achieved an overall **drag reduction of approximately 10.68%**, while reducing wall shear stress to **20.7 Pa** and lowering the drag coefficient to **0.0418**. Furthermore, the pumping power requirement decreased from **512 W** for the smooth-wall channel to **452 W**, corresponding to an energy saving of nearly **11.7%**. The hydraulic efficiency increased to **94.3%**, confirming the effectiveness of bio-inspired passive surface modification in improving fluid transport efficiency without requiring external energy input or additional mechanical devices.

The comparative evaluation further revealed that groove and micro-patterned textures also contributed to measurable reductions in pressure loss and wall friction; however, their performance remained slightly inferior to the optimized riblet geometry. The numerical results indicate that the dimensions and orientation of bio-inspired surface textures play a crucial role in controlling turbulence generation, pressure recovery, and boundary layer stability. Appropriate optimization of texture geometry can therefore maximize drag reduction while maintaining stable flow characteristics over a wide range of Reynolds numbers. These findings validate the application of biomimetic engineering principles in the design of energy-efficient internal flow systems.

Overall, the proposed numerical framework provides a reliable and efficient methodology for evaluating passive drag reduction technologies in engineering applications. The combination of bio-inspired surface engineering and advanced Computational Fluid Dynamics enables systematic optimization of internal flow channels for minimizing hydraulic losses and reducing operational energy consumption. The developed bio-inspired drag reduction strategy is highly suitable for **oil and gas transmission pipelines, chemical processing plants, compact heat exchangers, hydraulic machinery, cooling circuits, aerospace fuel transport systems, marine fluid networks, biomedical flow devices, microfluidic systems, water distribution pipelines, and advanced industrial fluid transport applications**, where improved hydraulic efficiency, lower pumping power, and sustainable energy utilization are essential.

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