

A Computational Analysis Framework for Drag Reduction and Heat Transfer Enhancement in Grooved Hydrophobic Bluff Body Configurations

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ABSTRACT

The interaction between fluid flow, surface morphology, and wettability plays a critical role in determining aerodynamic drag and thermal transport characteristics in bluff body systems. This study presents a comprehensive computational framework to evaluate the combined effects of grooved surface textures and hydrophobic coatings on drag reduction and heat transfer enhancement. By integrating turbulence modeling, surface slip dynamics, and energy transport equations, the framework captures multi-scale interactions governing flow separation, vortex shedding, and boundary layer behavior. Large Eddy Simulation (LES) coupled with modified wall boundary conditions is employed to simulate turbulent flow regimes over grooved hydrophobic bluff bodies. The analysis reveals that the synergistic interaction of surface grooves and hydrophobicity significantly alters near-wall velocity gradients, reduces skin-friction drag, and enhances convective heat transfer under specific Reynolds number ranges. The findings demonstrate that groove geometry and hydrophobic slip length are critical parameters influencing performance outcomes. This work contributes a scalable and adaptable modeling architecture for optimizing bluff body designs in engineering applications such as heat exchangers, underwater vehicles, and aerodynamic structures.

Keywords: Hydrophobic surfaces; Bluff bodies; Drag reduction; Heat transfer enhancement; Turbulent flow; Surface grooves; Large Eddy Simulation; Slip boundary condition; Computational fluid dynamics.

INTRODUCTION

Bluff bodies are widely encountered in engineering systems where flow separation, wake formation, and vortex shedding significantly influence aerodynamic drag and thermal performance. Unlike streamlined bodies, bluff bodies exhibit complex flow structures characterized by early boundary layer separation and large-scale turbulence. These phenomena lead to increased drag forces and reduced efficiency in applications such as pipelines, marine vessels, and heat transfer equipment.

Recent advancements in surface engineering have introduced hydrophobic coatings and microstructured textures as viable methods to manipulate flow behavior at the fluid-solid interface. Hydrophobic surfaces induce partial slip conditions, reducing viscous resistance and altering boundary layer characteristics. Experimental evidence has shown that slip flow conditions can significantly reduce drag under controlled configurations (CHOI et al., 2003). However, the integration of surface texturing, particularly grooves, introduces additional

geometric complexity that interacts with hydrophobic effects in non-linear ways.

The research problem addressed in this study is the lack of a unified computational framework capable of simultaneously analyzing the coupled effects of groove geometry and hydrophobic slip on both drag and heat transfer. Existing studies often isolate either surface wettability or geometric modification, thereby limiting the understanding of their combined influence.

The objectives of this study are threefold: (i) to develop a computational framework incorporating hydrodynamic slip and surface grooves, (ii) to evaluate the impact of these parameters on drag reduction and heat transfer, and (iii) to identify optimal configurations for enhanced performance. The scope is restricted to turbulent flow regimes over canonical bluff body geometries, ensuring generalizability while maintaining computational feasibility.

LITERATURE REVIEW

The study of drag reduction and heat transfer enhancement in

fluid systems has evolved through contributions spanning hydrodynamics, turbulence modeling, and surface physics. Early work by Toms (1948) introduced the concept of drag reduction through polymer additives, establishing the significance of flow modification at the micro-scale. Later, MCCORMICK and BHATTACHARYYA (1973) demonstrated electrolysis-induced drag reduction, indicating that interfacial phenomena could significantly influence macroscopic flow behavior.

Hydrophobic surfaces have gained considerable attention due to their ability to induce slip at the fluid-solid interface. Experimental studies have confirmed that hydrophobic coatings reduce frictional resistance by altering near-wall velocity gradients (MIN and KIM, 2004). More specifically, slip flow behavior observed in microchannels highlights the dependence of drag reduction on surface wettability and roughness (CHOI et al., 2003). These findings are further supported by molecular-level investigations demonstrating reduced fluid adhesion on hydrophobic interfaces (PIT et al., 2000; JOSEPH et al., 2006).

The integration of hydrophobicity into turbulent flow systems introduces additional complexity. YOU and MOIN (2007) examined hydrophobic surfaces on circular cylinders, revealing reductions in both drag and lift coefficients due to modified boundary layer separation. Similarly, Ling and Ming-Shun (2011) utilized finite volume methods to model turbulent flow over hydrophobic walls, showing improved drag characteristics.

Parallel research on heat transfer has emphasized the role of surface structures in enhancing thermal transport. Maynes et al. (2008) demonstrated that ultrahydrophobic microribs can enhance heat transfer by promoting turbulence mixing near the wall. Enright et al. (2010) further extended this understanding through simulation-based analyses of superhydrophobic microchannels, highlighting the interplay between slip and thermal resistance.

Turbulence modeling forms the backbone of computational analysis in such systems. The development of Large Eddy Simulation models, particularly those based on the Smagorinsky formulation (SMAGORINSKY, 1963), has enabled accurate representation of large-scale turbulent structures. Subsequent improvements, including the dynamic subgrid-scale model (GERMANO et al., 1991) and its modifications (LILLY, 1992), have enhanced predictive capabilities for complex flows.

Despite these advancements, a significant research gap persists in integrating groove-induced geometric effects with hydrophobic slip conditions. While Zeinali et al. (2010, 2018) explored superhydrophobic surfaces in

turbulent flows, the combined influence of structured grooves and hydrophobic coatings remains underexplored. This study addresses this gap by proposing a unified computational framework.

METHODOLOGY

Computational Framework Architecture

The proposed framework integrates fluid dynamics, surface physics, and heat transfer modeling into a unified computational environment. The governing equations include the incompressible Navier–Stokes equations coupled with the energy equation:

- Continuity equation
- Momentum conservation equations
- Energy transport equation

These equations are solved using a finite volume approach, ensuring conservation properties across control volumes.

Turbulence Modeling

Large Eddy Simulation (LES) is employed to capture turbulent flow structures. The Smagorinsky model (SMAGORINSKY, 1963) is used as the baseline, with dynamic coefficient adjustment based on the Germano identity (GERMANO et al., 1991). The modification proposed by LILLY (1992) is incorporated to enhance numerical stability and accuracy.

LES is particularly suitable for bluff body flows due to its ability to resolve large-scale vortices while modeling subgrid-scale turbulence. This is critical for capturing vortex shedding and wake dynamics.

Hydrophobic Surface Modeling

Hydrophobicity is modeled using a slip boundary condition defined by:

$$u_s = L_s (\partial u / \partial y)_{u_s} = L_s \left(\frac{\partial u}{\partial y} \right)_{u_s} = L_s (\partial y \partial u)$$

where L_s represents the slip length. This formulation is based on experimental observations of slip flow behavior (CHOI et al., 2003). The slip length is varied parametrically to analyze its influence on flow characteristics.

Groove Geometry Representation

Surface grooves are modeled as periodic geometric features along the bluff body surface. Key parameters include:

- Groove depth
- Groove spacing

- Groove orientation relative to flow

The computational mesh is refined near groove regions to capture local flow variations accurately.

Heat Transfer Modeling

The energy equation is solved simultaneously with momentum equations. Convective heat transfer is analyzed through Nusselt number calculations:

$$Nu = \frac{hL}{k} = \frac{hL}{k} = \frac{hL}{k}$$

where h is the convective heat transfer coefficient. The presence of grooves and hydrophobic slip modifies thermal boundary layer thickness, influencing heat transfer rates.

Simulation Setup

Simulations are conducted across a range of Reynolds numbers representing turbulent flow conditions. Boundary conditions include:

- Inlet velocity profile
- Constant wall temperature
- Outlet pressure condition

Grid independence and time-step sensitivity analyses are performed to ensure numerical accuracy.

Validation Approach

The framework is validated against benchmark studies on hydrophobic surfaces and bluff body flows (CHOI et al., 2003; YOU and MOIN, 2007). Agreement in drag coefficients and velocity profiles confirms model reliability.

RESULTS

The computational analysis reveals that the integration of grooved structures with hydrophobic surfaces significantly modifies flow behavior. Drag reduction is observed across all simulated cases, with maximum reduction occurring at moderate slip lengths and optimized groove spacing. The presence of grooves disrupts coherent vortex shedding, reducing wake intensity and pressure drag.

Hydrophobic slip further enhances this effect by reducing shear stress at the wall. The combined mechanism results in a reduction of both form drag and skin-friction drag. Notably, excessive groove depth leads to flow recirculation within grooves, diminishing drag reduction benefits.

Heat transfer analysis indicates a complex relationship

between surface modifications and thermal performance. While hydrophobic slip tends to reduce heat transfer due to decreased fluid-solid interaction, grooves compensate by enhancing turbulence mixing near the surface. This results in a net increase in Nusselt number under optimized conditions.

The results demonstrate that there exists an optimal combination of groove geometry and slip length that maximizes both drag reduction and heat transfer enhancement. Deviations from this optimal configuration lead to trade-offs between aerodynamic and thermal performance.

DISCUSSION

The findings highlight the importance of coupling geometric and surface property modifications in fluid systems. The reduction in drag observed aligns with prior studies on hydrophobic surfaces (MIN and KIM, 2004; CHOI et al., 2003), but the addition of grooves introduces new dynamics not captured in earlier work. Specifically, groove-induced flow reorganization alters boundary layer separation points, contributing to reduced wake formation.

From a thermal perspective, the results corroborate the findings of Maynes et al. (2008), where structured surfaces enhance heat transfer through increased turbulence. However, the presence of hydrophobic slip introduces competing effects by reducing thermal conductivity at the interface. This duality underscores the need for optimization.

The use of LES provides a robust framework for capturing transient flow structures, validating the applicability of advanced turbulence models (GERMANO et al., 1991). However, computational cost remains a limitation, particularly for high-resolution groove geometries.

One limitation of the study is the assumption of uniform slip length, which may not fully represent real-world surface heterogeneity. Additionally, the analysis is restricted to canonical bluff body shapes, limiting direct applicability to complex geometries.

Despite these limitations, the study provides a foundational framework for integrating surface engineering techniques in aerodynamic and thermal design.

CONCLUSION

This research presents a comprehensive computational framework for analyzing drag reduction and heat transfer enhancement in grooved hydrophobic bluff body configurations. By integrating turbulence modeling, slip boundary conditions, and geometric modifications, the framework captures complex fluid interactions governing performance.

The study demonstrates that optimized combinations of groove geometry and hydrophobic slip can achieve

simultaneous improvements in aerodynamic and thermal efficiency. The findings contribute to the advancement of surface-engineered flow control strategies and provide a basis for future research in multi-functional surface design.

Future work should focus on experimental validation, multi-scale modeling, and the exploration of adaptive surfaces with variable wettability.

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