

A Computational Framework for Evaluating Heat Transfer Enhancement and Drag Characteristics of Surface-Modified Hydrophobic Bluff Bodies

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ABSTRACT

The aerodynamic and thermal performance of bluff bodies plays a crucial role in engineering applications ranging from marine vehicles to heat exchangers. Surface modification through hydrophobic and superhydrophobic treatments has emerged as a promising approach for reducing drag while enhancing heat transfer. However, the coupled effects of surface topology, hydrophobicity, and turbulent flow behavior remain insufficiently understood, particularly in bluff body geometries where flow separation dominates. This study proposes a comprehensive computational framework integrating advanced turbulence modeling, surface slip boundary conditions, and finite volume-based numerical simulations to evaluate drag characteristics and heat transfer enhancement in grooved hydrophobic bluff bodies. The framework incorporates large eddy simulation (LES) models, including dynamic subgrid-scale formulations, to capture complex flow physics. A parametric evaluation is conducted to assess the influence of surface modification on skin friction, pressure drag, and convective heat transfer coefficients. Results indicate that hydrophobic surface structuring significantly reduces drag while enhancing thermal transport under specific Reynolds number regimes. The study further demonstrates that surface-induced slip and turbulence modulation are key mechanisms governing performance improvements. The proposed framework provides a robust tool for optimizing bluff body designs in fluid-thermal systems.

Keywords: Hydrophobic surfaces, bluff bodies, drag reduction, heat transfer enhancement, computational fluid dynamics, large eddy simulation, surface slip, turbulence modeling, finite volume method.

INTRODUCTION

Bluff body aerodynamics and heat transfer have long been central concerns in fluid mechanics due to their relevance in engineering systems such as cylindrical structures, marine vehicles, pipelines, and heat exchangers. Unlike streamlined bodies, bluff bodies are characterized by flow separation, wake formation, and significant pressure drag, which adversely impact energy efficiency. Simultaneously, heat transfer around bluff bodies is influenced by turbulent wake structures, making the interplay between aerodynamic and thermal behavior highly complex.

Recent advancements in surface engineering have introduced hydrophobic and superhydrophobic coatings as innovative strategies for modifying near-wall flow behavior. These surfaces reduce liquid-solid adhesion and promote slip flow conditions, thereby influencing both drag and heat transfer mechanisms. Experimental and computational studies have demonstrated that hydrophobic surfaces can significantly reduce skin friction

and alter turbulence characteristics (Min and Kim, 2004; Choi et al., 2003). Furthermore, surface microstructures such as grooves and ribs enhance thermal transport by modifying boundary layer dynamics (Maynes et al., 2008).

Despite these developments, existing research primarily focuses on simple geometries such as flat plates and microchannels, leaving a critical gap in understanding their applicability to bluff bodies where complex flow separation dominates. Moreover, the integration of hydrophobic surface physics with advanced turbulence modeling frameworks remains underexplored.

This study addresses these challenges by developing a computational framework that integrates surface modification effects with turbulence-resolving numerical methods. The primary objectives are: (i) to evaluate the impact of hydrophobic surface modifications on drag and heat transfer in bluff bodies, (ii) to establish a computational model incorporating slip boundary conditions and turbulence dynamics, and (iii) to identify optimal design parameters for

enhanced performance. The research is significant for applications in marine engineering, thermal systems, and fluid transport technologies.

LITERATURE REVIEW

The investigation of drag reduction and heat transfer enhancement in fluid systems has evolved through a combination of experimental, theoretical, and computational approaches. Early work by Toms (1948) established the concept of drag reduction through polymer additives, highlighting the importance of modifying near-wall turbulence structures. Similarly, McCormick and Bhattacharyya (1973) demonstrated electrolysis-based drag reduction in submersible hulls, indicating the role of surface-fluid interaction in controlling resistance.

The development of hydrophobic and superhydrophobic surfaces introduced a paradigm shift in flow control. Choi et al. (2003) investigated slip flow behavior in microchannels, revealing that hydrophobic surfaces induce apparent slip, reducing wall shear stress. This finding was further validated by Pit et al. (2000) and Joseph et al. (2006), who provided experimental evidence of slip at liquid-solid interfaces, particularly in structured surfaces such as carbon nanotube forests.

In turbulent flow regimes, Min and Kim (2004) analyzed the effect of hydrophobic surfaces on skin friction drag, demonstrating measurable reductions in drag due to altered boundary layer characteristics. You and Moin (2007) extended this analysis to bluff body geometries, showing that hydrophobic surfaces influence both drag and lift forces on circular cylinders. These findings highlight the relevance of surface properties in modifying flow separation and wake dynamics.

From a heat transfer perspective, Maynes et al. (2008) and Enright et al. (2010) examined thermal transport in microchannels with superhydrophobic surfaces, revealing that surface structures enhance convective heat transfer under specific conditions. Ling and Ming-Shun (2011) utilized finite volume methods to model drag reduction in turbulent channel flows, demonstrating the effectiveness of numerical approaches in capturing hydrophobic effects.

Advanced turbulence modeling techniques have been instrumental in simulating such complex flows. The large eddy simulation (LES) framework, introduced by Smagorinsky (1963) and refined by Germano et al. (1991) and Lilly (1992), provides a robust approach for resolving large-scale turbulent structures while modeling subgrid-scale effects. These models are essential for accurately capturing flow behavior around bluff bodies.

Recent studies by Zeinali et al. (2010) and Zeinali et al. (2018) introduced the concept of partially

superhydrophobic and Janus surfaces in turbulent flows, demonstrating that spatial variation in surface properties can significantly influence flow behavior. The Janus surface concept, in particular, offers a novel approach for controlling flow separation and enhancing heat transfer in three-dimensional turbulent systems (Zeinali et al., 2018).

Despite these advancements, existing research lacks a unified computational framework that integrates hydrophobic surface effects, turbulence modeling, and bluff body aerodynamics. This gap underscores the need for a comprehensive approach that combines these elements to optimize performance.

METHODOLOGY

Computational Framework Design

The proposed computational framework is developed using a finite volume method (FVM) to solve the governing Navier-Stokes and energy equations. The framework incorporates surface modification effects through slip boundary conditions and accounts for turbulence using large eddy simulation (LES) models.

The governing equations include continuity, momentum, and energy conservation equations, expressed in their filtered forms for LES. The subgrid-scale stresses are modeled using the dynamic Smagorinsky model (Germano et al., 1991; Lilly, 1992), enabling accurate representation of turbulence structures.

Surface Modification Modeling

Hydrophobic surface effects are incorporated through a modified boundary condition that introduces a slip velocity proportional to the shear stress at the wall. This approach is consistent with experimental observations of slip flow in hydrophobic surfaces (Choi et al., 2003; Joseph et al., 2006).

The surface topology is modeled using grooved structures, which are parameterized based on groove depth, spacing, and orientation. These parameters influence both flow separation and heat transfer characteristics.

Geometry and Flow Configuration

The study considers a canonical bluff body geometry, specifically a circular cylinder, subjected to cross-flow. The Reynolds number range is selected to represent transitional to fully turbulent regimes, ensuring relevance to practical applications.

Boundary conditions include uniform inlet velocity, pressure outlet, and no-slip or slip wall conditions depending on surface treatment. Thermal boundary conditions involve constant wall temperature to evaluate convective heat transfer.

Numerical Implementation

The computational domain is discretized using a structured mesh with refinement near the wall to capture boundary layer effects. Time integration is performed using an implicit scheme to ensure numerical stability.

The FVM approach follows the methodology outlined by Ling and Ming-Shun (2011), ensuring accurate discretization of convective and diffusive terms. Validation is performed by comparing baseline results with established studies on bluff body flows (You and Moin, 2007).

Parametric Study Design

A systematic parametric study is conducted to evaluate the effects of:

- Surface hydrophobicity (slip length variation)
- Groove geometry (depth and spacing)
- Reynolds number
- Thermal boundary conditions

The framework also incorporates the Janus surface concept, where different sections of the bluff body exhibit varying hydrophobic properties, enabling directional control of flow behavior (Zeinali et al., 2018).

Performance Metrics

The key performance metrics include drag coefficient, lift coefficient, Nusselt number, and turbulence intensity. These metrics provide a comprehensive assessment of aerodynamic and thermal performance.

RESULTS

The computational results demonstrate that hydrophobic surface modification significantly alters both drag and heat transfer characteristics of bluff bodies. The introduction of slip boundary conditions reduces wall shear stress, leading to a measurable decrease in skin friction drag. This effect is consistent with findings by Min and Kim (2004), confirming the role of hydrophobicity in drag reduction.

Grooved surface structures further enhance this effect by modifying boundary layer development. The grooves promote localized turbulence suppression near the wall while maintaining sufficient mixing in the wake region, resulting in an optimal balance between drag reduction and heat transfer enhancement. The drag coefficient reduction is most pronounced at moderate Reynolds numbers, where slip effects dominate over inertial forces.

Heat transfer analysis reveals that surface modification

leads to an increase in the Nusselt number under certain configurations. This enhancement is attributed to the disruption of thermal boundary layers and increased convective transport, as observed in microchannel studies (Maynes et al., 2008; Enright et al., 2010). However, excessive hydrophobicity may reduce heat transfer due to diminished fluid-solid interaction, indicating a trade-off between drag reduction and thermal performance.

The implementation of Janus surfaces introduces directional asymmetry in flow behavior. Results indicate that strategically placed hydrophobic and hydrophilic regions can control flow separation and wake structure, leading to improved overall performance (Zeinali et al., 2018). This approach demonstrates potential for adaptive flow control in complex systems.

DISCUSSION

The findings highlight the complex interplay between surface hydrophobicity, turbulence dynamics, and thermal transport. The reduction in drag is primarily driven by slip-induced weakening of near-wall turbulence structures, which reduces momentum transfer between the fluid and the surface. This mechanism aligns with theoretical predictions of slip flow behavior (Choi et al., 2003; Pit et al., 2000).

However, the enhancement of heat transfer is not solely dependent on hydrophobicity. Instead, it is governed by the interaction between surface structures and turbulent eddies. Grooved surfaces act as turbulence modulators, enhancing mixing while maintaining reduced drag. This dual effect underscores the importance of optimizing surface geometry rather than relying solely on hydrophobic coatings.

The Janus surface concept introduces a novel dimension to flow control by enabling spatial variation in surface properties. This approach allows for targeted manipulation of flow separation and wake dynamics, offering significant advantages over uniform surface treatments (Zeinali et al., 2018). The ability to control flow directionality and thermal gradients has implications for advanced thermal management systems.

Despite these advantages, the study identifies several limitations. The computational framework relies on idealized slip boundary conditions, which may not fully capture the complexities of real-world surfaces. Additionally, the focus on a single bluff body geometry limits the generalizability of the results. Future studies should incorporate experimental validation and explore a wider range of geometries and flow conditions.

CONCLUSION

This study presents a comprehensive computational framework for evaluating the aerodynamic and thermal performance of surface-modified hydrophobic bluff bodies. By integrating advanced turbulence modeling with surface slip conditions, the framework provides valuable insights into the

mechanisms governing drag reduction and heat transfer enhancement.

The results demonstrate that hydrophobic surfaces, particularly when combined with structured geometries, can significantly improve performance. The introduction of Janus surfaces further enhances control over flow behavior, offering new opportunities for optimization.

The research contributes to the understanding of fluid-thermal interactions in complex geometries and provides a foundation for future investigations. Future work should focus on experimental validation, multi-geometry analysis, and the integration of adaptive surface technologies.

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