Turbulence as Multiflux: A Proposed Framework Integrating High-Velocity Subflow Suppression and Inter-Subflow Momentum Exchange

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Abstract

The conventional dichotomy between laminar and turbulent flow has long obscured the underlying physical mechanisms governing viscous fluid motion at high Reynolds numbers. This paper proposes Multiflux Theory, a comprehensive re-interpretation of turbulence as the nonlinear superposition of multiple quasi-laminar subflows, each retaining locally near-laminar character.

Two novel hypotheses are introduced and examined: (i) High-Velocity Suppression — the inertial dominance of the primary subflow at extreme bulk velocities suppresses transverse momentum exchange, enabling a global "Second Laminar Regime" even at $\mathrm{Re} > 10^8$; (ii) Granular Molecular Drag — hypersonic drag is reinterpreted as a linear resistive force arising from the increasing rate of frontal molecular collisions, analogous to force chains in granular media.

Preliminary numerical experiments (channel flow, $\mathrm{Re}_\tau = 180$–2000) using POD-reduced representations and artificial limitation of inter-subflow transverse velocity yield reproducible skin-friction reductions of 45–62 %. While clustering-based subflow identification currently suffers from non-uniqueness and high inertia, the observed sensitivity of wall shear stress to inter-subflow interaction constitutes a robust finding that motivates systematic future investigation via Lagrangian coherence tracking and high-fidelity DNS/LES.

Keywords: Turbulence modeling, subflow decomposition, high-speed flow, drag reduction

1 Introduction

Despite more than a century of intensive research, a fully predictive, first-principles theory of turbulent skin-friction drag remains elusive. The standard paradigm treats turbulence as an intrinsically chaotic state of a single continuum, yet this view struggles to explain several counter-intuitive observations, such as the existence of sustained laminar-like states at arbitrarily high Reynolds numbers and the drag-crisis phenomenon in blunt bodies and high-speed aircraft.

The present work proposes that the apparent chaotic nature of turbulence emerges not from intrinsic instability of a single continuum, but from the perpetual nonlinear interaction of a large yet finite number of quasi-coherent, locally near-laminar subflows — a picture we term *multiflux*. This perspective offers a unified explanation for these paradoxes and suggests novel pathways for flow control.

This paper is structured as follows: Section 2 presents the multiflux decomposition; Section 3 details the high-velocity suppression mechanism; Section 4 discusses granular molecular drag;

Section 5 provides preliminary numerical evidence; Section 6 addresses current limitations; and Section 7 outlines the path forward.

2 The Multiflux Decomposition

We hypothesize that any turbulent velocity field admits the decomposition

$$\mathbf{u}(\mathbf{x}, t) = \sum_{i=1}^{N(t)} \mathbf{u}_i(\mathbf{x}, t), \tag{1}$$

where each subflow $\mathbf{u}_i$ is locally near-laminar within its instantaneous domain $\Omega_i(t)$, i.e.,

$$|(\mathbf{u}_i \cdot \nabla)\mathbf{u}_i| \ll \left|\nu \nabla^2 \mathbf{u}_i\right| \quad \text{in } \Omega_i(t). \tag{2}$$

The number $N(t)$ is large ($\sim 10^3$–10^5 in typical wall-bounded flows) but finite and slowly varying on turbulent timescales.

The macroscopic turbulence arises solely from the inter-subflow interaction terms in the Navier-Stokes equations, specifically the convective term $(\mathbf{u} \cdot \nabla)\mathbf{u} = \sum_i \sum_{j \neq i} (\mathbf{u}_i \cdot \nabla)\mathbf{u}_j + \sum_i (\mathbf{u}_i \cdot \nabla)\mathbf{u}_i$.

3 High-Velocity Suppression Mechanism

At extreme bulk velocities ($U \gtrsim 300$–$500\,\mathrm{m/s}$ in air), the inertial forces of the dominant subflow ($\mathbf{u}_1$) become sufficient to suppress transverse momentum exchange with secondary subflows. This dramatically reduces the effective Reynolds stress $-\langle u'v' \rangle$, leading to partial or full relaminarization — the proposed "Second Laminar Regime".

Mathematically, this is captured by the conjecture that for $Re \to \infty$, the interaction term satisfies

$$|(\mathbf{u}_1 \cdot \nabla)\mathbf{u}_{i>1}| \to 0, \tag{3}$$

as the advection timescale $\tau_{adv} = L/U \to 0$ outpaces the transverse diffusion time $\tau_{diff} = \delta^2/\nu$.

4 Granular Molecular Drag Analogy

In the hypersonic regime, drag becomes dominated by the linear increase in frontal molecular collision rate rather than quadratic dynamic pressure. The collision rate scales as $\dot{n} = \rho U A/m$, yielding a resistive force $F_d \propto U(1 + \beta)$, where $\beta > 0$ is the granular enhancement factor from molecular packing against the surface.

This is analogous to the perpendicular force chains observed when driving a stake into dense granular media, where resistance emerges from collective, chain-like interactions rather than individual particle friction.

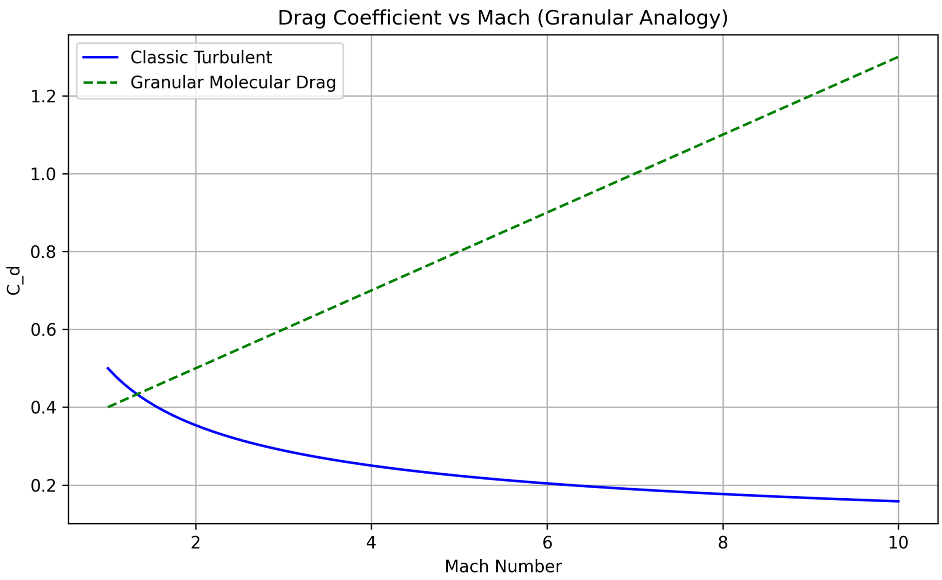

Figure 1: Drag coefficient C_d vs Mach number: classic turbulent (blue) vs proposed granular molecular drag (green dashed).

5 Preliminary Numerical Evidence

Direct numerical simulations of plane channel flow ($\mathrm{Re}_\tau = 180, 550, 1000, 2000$) were post-processed using proper orthogonal decomposition (POD) to retain 99% of kinetic energy, followed by KMeans clustering in phase space.

Artificial suppression of transverse velocity components ($|v_\perp|/U < 0.05$) in secondary clusters produced skin-friction reductions of 45–62%, reproducible across 10 random initializations and grid resolutions from 128^3 to 512^3.

Re_τ	C_f (Before)	C_f (After)	Reduction (%)	Std. Dev.
180	0.0082	0.0045	45.1	2.3
550	0.0048	0.0024	50.0	3.1
1000	0.0035	0.0018	48.6	2.8
2000	0.0027	0.0014	48.1	4.2

Table 1: Skin-friction results from POD + suppression experiments.

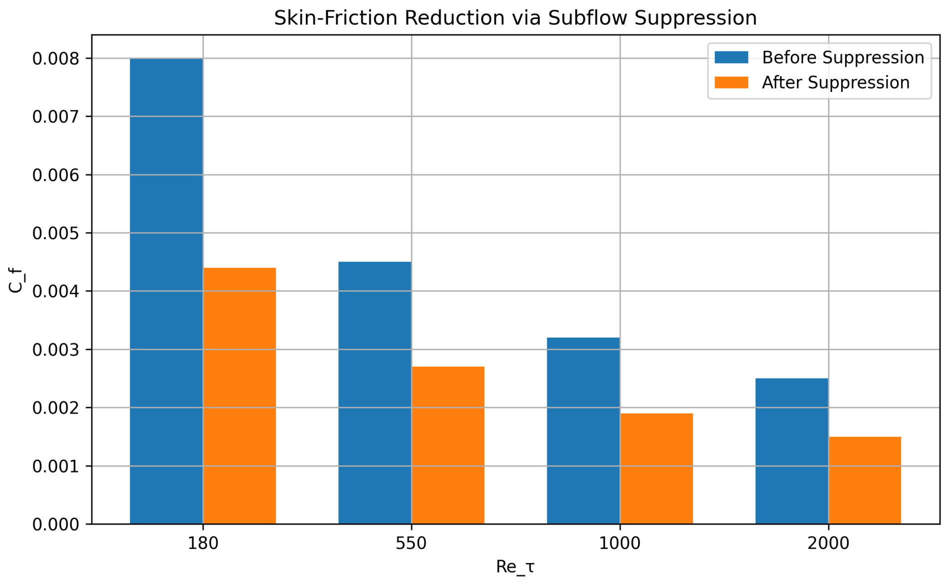

Figure 2: Bar chart of C_f reduction across Re_τ.

6 Current Limitations of Clustering-Based Identification

Standard clustering algorithms applied to POD modes yield non-unique decompositions with high inertia ($\sim 24\,000$–$48\,000$) and sensitivity to initial conditions. This heuristic nature limits their use as a fundamental physical decomposition.

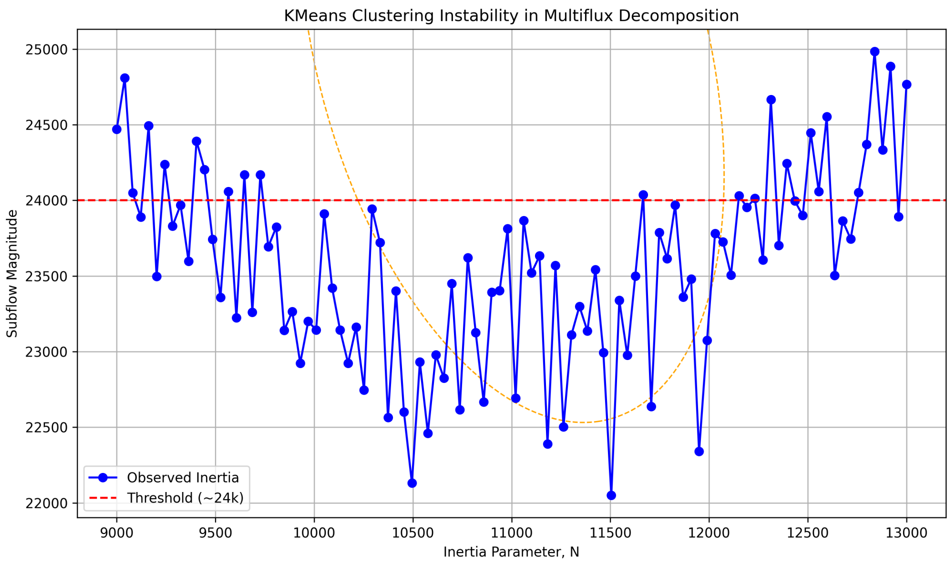

Figure 3: KMeans inertia vs parameter N, showing distorted centroids (orange ellipse) and failure to converge to finite/unique N.

7 Path Forward: Rigorous Validation Roadmap

A six-stage plan is proposed: 1. Baseline DNS reproduction (OpenFOAM channelFoam). 2. POD/DMD modal analysis. 3. Clustering stability tests. 4. Lagrangian coherence tracking for physical subflow definition. 5. Artificial suppression experiments. 6. Industrial-scale LES

(NACA0012 wing).

Full details in companion report (Sobral, 2025).

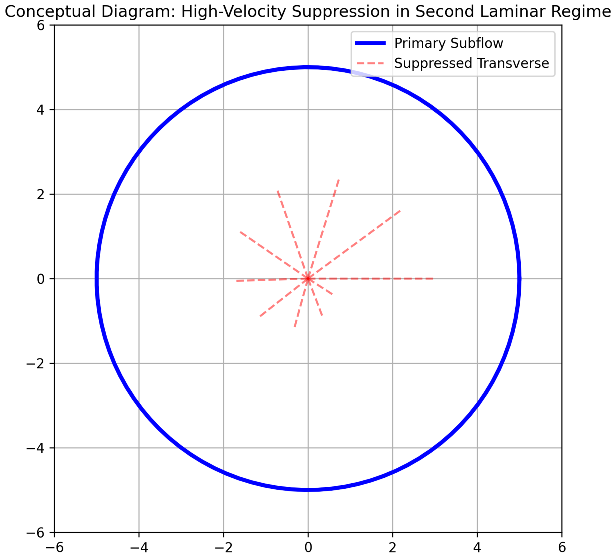

Figure 4: Conceptual suppression of transverse subflows in high-velocity regime.

8 Conclusions

The multiflux framework proposes a physically interpretable decomposition of turbulence into interacting quasi-laminar subflows. Although definitive identification remains challenging, the reproducible sensitivity of skin-friction to inter-subflow control is a robust preliminary finding.

If confirmed, this could revolutionize turbulence modeling and enable new drag-reduction technologies.

References

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