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Plasma Activated Boundary Layer Control for Hypersonic Transition Delay: A Theoretical and Numerical Investigation

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Abstract: ***Laminar-to-turbulent transition in hypersonic boundary layers results in a significant increase in surface heat flux and skin friction, posing a critical challenge for the design of hypersonic vehicles. This paper theoretically investigates the potential of Plasma-Activated Kinetics (PAK) as a novel active flow control technique for hypersonic transition delay. We propose that energy deposition from a non-thermal, nanosecond-pulsed dielectric barrier discharge (ns-DBD) plasma actuator can strategically alter the boundary layer's stability landscape. Through a multi-physics framework, we analyse three primary mechanisms: (1) the creation of a localised, steady thermal bump that modifies the base floe profile, (2) the generation of stabilising species gradients (vibrational non-equilibrium) that regulate the Mack mode stability, and (3) the direct damping of the second-mode instability waves through periodic, anti-phase thermal perturbations. Linear stability theory (LST) and parabolized stability equation (PSE) analyses are employed to quantify the increase in transition Reynolds number. Theoretical results imply that PAK, by selectively targeting the most unstable modes (in particular the second mode), can attain an enormous downstream shift in transition location (>30% increase in transition Reynolds number) with minimal energy input compared to standard thermal safety systems. This work establishes a foundational theoretical basis for PAK as a promising technology for enhancing hypersonic vehicle performance and thermal control.***
Keywords: Hypersonic Boundary Layers, Laminar-to-Turbulent Transition, Plasma activated kinetics, Nanosecond Pulsed DBD Actuator, Second Mode Instability Control, Liner Stability Analysis

I. INTRODUCTION

The control of boundary-layer transition is a critical challenge in hypersonic flight (M > 5). A turbulent boundary layer can result in heat transfer rates an order of magnitude higher than its laminar counterpart, severely impacting thermal protection system (TPS) design, vehicle range, and structural integrity [1]. Passive techniques, such as wall cooling or surface polishing, have practical limitations; consequently, active flow control techniques capable of adapting to varying flight conditions are highly desirable. Recent advances in plasma physics have opened new avenues for active flow control. Plasma actuators—particularly Dielectric Barrier Discharge (DBD) devices—offer rapid response times, no moving parts, and the ability to impart momentum or energy directly into the flow [2]. In low-velocity flows, alternating current DBD (AC-DBD) actuators are well-established for separation control. However, for high-velocity applications, the dominant control mechanism shifts from momentum addition to thermal energy deposition due to compressibility effects. Nanosecond-pulsed DBDs (ns-DBDs) are particularly well-suited for this, as they produce rapid, localized heating (μs) without significant fluid displacement [3].

This paper explores the theoretical underpinnings of using Plasma-Activated Kinetics (PAK) for hypersonic transition delay. We posit that strategic, localized energy deposition from an ns-DBD can modify boundary-layer stability characteristics to suppress dominant instability modes. The study dissects this problem through three core theoretical sections: the amendment of the base flow, the stabilization of Mack modes via species gradients, and the direct wave cancellation of second-mode instabilities. Finally, the theoretical framework, a consolidated discussion of results, and concluding remarks are provided.

II. THEORETICAL CONTENT

A. Base Flow Modification via Steady Thermal Perturbation

The primary effect of a continuous (or high-frequency pulsed) ns-DBD actuator is the creation of a localized "thermal bump" at the surface. This is modelled as a region of elevated wall temperature over a finite streamwise extent [3]. This rapid heating—on the order of several hundred Kelvin within microseconds—directly modifies the near-wall fluid properties.

Specifically, the heated wall decreases the local density and increases the molecular viscosity (following Sutherland's Law**)**. These variations alter the Blasius or Falkner-Skan-Cooke similarity solutions governing the laminar base flow [6]. The increase in viscosity thickens the viscous sublayer, while the reduced density steepens the velocity gradient near the wall but relaxes the overall u(y) profile further out.

Critically, this modification reduces the curvature $\delta^2 u/\delta y^2$ in the outer region of the boundary layer, making the profile less inflectional. A less inflectional profile is more stable to inviscid instability mechanisms, which require an inflection point according to Rayleigh's criterion [4, 6]. In hypersonic flows, this directly targets the first mode (the compressible analogue of the Tollmien-Schlichting **wave**), which often exhibits an inviscid, inflectional character, particularly over adiabatic or cooled walls [1, 6].The stabilizing effect can be rigorously quantified by examining the displacement of the generalized inflection point, defined as:

$$\frac{\partial}{\partial y}\left(\rho \frac{\partial u}{\partial y}\right) = 0$$

A downstream shift or weakening of this inflection point reduces the production term P in the disturbance kinetic energy equation. This results in lower temporal growth rates (α_i) and a contraction of the neutral stability curve in the plane [6]. Consequently, the N-factor integration required to reach the critical transition threshold occurs over a significantly longer streamwise distance, effectively delaying the onset of turbulence [1].

TABLE I
THEORETICAL PARAMETERS AND IMPACT OF A LOCALIZED THERMAL BUMP ON BOUNDARY LAYER PROFILES

SNo	Parameter	Symbol	Unperturbed(Laminar) Flow	With Plasma-Induced Thermal Bump	Theoretical Stabilizing Mechanism
1	Wall Temperature Ratio	T_w/T_∞	0.8 (Cooled Wall)	1.2 (Local Heated Strip)	Reduces Near-Wall Density Gradient
2	Local Mach Number Profile	M(y)	Steep gradient near wall	Smoothed, less steep gradient	Weakens the generalized inflection point
3	Shape Factor	H	~2.2 – 2.5 (for hypersonic)	Increases slightly	Indicates a fuller velocity profile, less prone to separation and instability
4	Neutral Stability Curve (1st Mode)	$R_{e\partial}*$, M	Branch I at $R_{e\partial} * \approx 500$	Branch I shifts to $R_{e\partial} * \approx 700$	Increase critical Reynolds number for first-mode instability
5	Key governing relation		Falkner-Skan-Cooke	Modified by $\mu(T) \propto T_w$	Increased viscosity

B. Stabilization of Mack Modes via Vibrational Nonequilibrium

At hypersonic speeds, the dominant instability is often the second mode (or Mack mode), which is essentially a trapped acoustic wave that resonates between the wall and the sonic line [4]. This mode is extremely sensitive to the temperature and species profiles within the boundary layer. An ns-DBD plasma in air generates reactive species (such as O, N, NO, N_2^+, O_2^-) and, more importantly, deposits a significant fraction of energy into the vibrational modes of N_2 and O_2. This creates a state of vibrational nonequilibrium ($T_{vib}>T_{trans}$)) that persists for several milliseconds downstream of the actuator.

The gradient of vibrational temperature, $\partial T_{vib}/\partial y$, alters the effective speed of sound profile within the boundary layer. Since the second mode relies on the acoustic properties of the "waveguide" formed between the wall and the sonic line, this modification affects its phase speed and growth rate. Theoretical analysis using a multi-temperature Linear Stability Theory (LST) framework shows that a sufficiently large, $T_{vib}/\partial y$, near the critical layer can "detune" the resonance condition of the second mode. This detuning leads to substantial stabilization and a reduction in the maximum amplification rate [5].

TABLE II
INFLUENCE OF PLASMA-GENERATED SPECIES/VIBRATIONAL NON-EQUILIBRIUM ON MACK MODE STABILITY

SNo	Plasma-Activated Parameter	Typical Scale (Theoretical)	Region of Max Effect	Impact on Mack Mode (f~$100-300\ kHz$)	Theoretical Justification
1	Vibrational Temperature gradient	$\Delta T_{vib} \approx 500-1000K$	Inner 30% of the boundary layer	Reduction in growth rate, -$\Delta\alpha \approx 20-40\%$	Alters local sound speed, shifting the resonance condition of the trapped wave
2	Atomic Oxygen Mass Fraction	[O] $\approx 0.01-0.06$	Near-wall region	Modifies mean density profile; can stabilize or destabilize depending on gradient sign	Changes mixture specific heat ratio γ and density ρ affecting wave propagation
3	Characteristic Relaxation Length	L_{vib}~$10-50\ mm$	Downstream of the actuator	Provides a persistent stabilization zone beyond the physical actuator location	Slow relaxation of vibrational energy provides a “tail” of stability influence

C. *Active Wave Cancellation through Unsteady Thermal Forcing*

The most advanced application of Plasma-Activated Kinetics (PAK) involves operating the plasma actuator in a closed-loop, high-frequency pulsed mode [7]. The actuator is driven at the same frequency as the detected instability but with a precisely managed phase shift ($\Delta\phi \approx 180^o$). The ns-DBD’s ultra-fast heating generates a volumetric, localized transient wave**,** thermal perturbation resulting from rapid energy deposition that interacts with the incoming instability wave [3, 7]. When this artificially generated perturbation is anti-phased with the pressure fluctuations of the natural instability, destructive interference occurs, leading to a net damping of the wave amplitude. This process is analogous to active noise cancellation applied within the boundary layer.
The effectiveness of this technique relies critically on three factors:

1) Actuator Bandwidth: The actuator's response time must be significantly shorter than the period of the instability. To achieve cancellation of an instability wave with a dominant frequency $f_{instability}$, actuator must be capable of pulsing at frequencies f_{pulse} / $f_{instability}$ with sub-microsecond precision to maintain phase authority.
2) Accuracy of Phase Detection and Compensation: The closed-loop control system must accurately measure the phase of the incoming wave at an upstream sensor and apply the corrective signal at the actuator location. This requires compensating for the convective delay—the time it takes for the instability wave to travel from the sensor to the actuator at the group velocity $v_{g.}$
3) Spatial Coupling: This describes how well the physical shape and placement of the plasma-induced thermal perturbation matches the spatial structure of the instability wave within the boundary layer [8]. Optimal coupling ensures that the energy is deposited exactly where the instability amplitude is highest, maximizing the damping effect.

III. MATERIALS AND METHODOLOGY

In this theoretical investigation, we use a hierarchical, multi-stage methodology to analyze how Plasma-Activated Kinetics (PAK) influences the stability of hypersonic boundary layers. The process begins by establishing a baseline flow, where we compute steady, two-dimensional boundary layer profiles over flat plates or wedges. This is achieved by combining self-similar solutions with high-fidelity Computational Fluid Dynamics (CFD) of the compressible Navier-Stokes equations. By assuming the inflow is in chemical and vibrational equilibrium, we create a controlled, undisturbed laminar state that serves as the benchmark for assessing any plasma-induced changes. Once the baseline is set, we mathematically model the plasma actuator’s influence. We represent the effect of a nanosecond-pulsed Dielectric Barrier Discharge (ns-DBD) as a time-dependent volumetric energy source within the momentum and energy equations. For steady-state studies, such as analyzing a time-averaged "thermal bump," we approximate this as a localized heat flux on the wall surface. To account for specific molecular changes, we implement a two-temperature model that distinguishes between translational-rotational temperatures (T_{trans}) and vibrational temperature (T_{vib}). This model allows us to couple the flow equations with source terms for vibrational excitation, relaxation, and dissociation, providing a clear view of how plasma-generated species gradients behave.

The third stage involves a rigorous stability analysis of these modified boundary layers. We apply Linear Stability Theory (LST) to the base flows to identify the growth rates of dominant instability modes, specifically the first (Tollmien-Schlichting) and second (Mack) modes. To account for how these disturbances evolve in non-parallel flows as they move downstream, we use the more advanced Parabolized Stability Equations (PSE). We then quantify the transition from laminar to turbulent flow using the N-factor method, where the spatial growth rate ($-\alpha_i$) is integrated from the neutral point,

$$N = \int -\alpha_i \, dx$$

In this framework, transition is typically assumed to occur when the N-factor reaches a critical threshold between 6 and 10.

Finally, we investigate the potential for active wave cancellation through a dedicated interaction model. Here, the high-frequency pulsed plasma actuator is modelled as a forced harmonic disturbance introduced at the wall. We analyze its interaction with naturally occurring instability waves within a spatial linear growth framework. By summing the complex amplitudes of the natural wave and the anti-phased plasma forcing, we can determine the net damping or amplification. This provides the theoretical foundation for determining whether closed-loop control is a viable way to maintain stable hypersonic flight.

IV. RESULTS AND DISCUSSIONS

The theoretical implementation of the described models provides consolidated insights into the efficacy and synergy of plasma-based control strategies. Analysis indicates that steady heating is most effective against first-mode instabilities, which typically dominate at lower hypersonic Mach numbers or over highly cooled surfaces; specifically, increasing the local wall temperature ratio (T_w / T_∞) from 0.8 to 1.2 delays first-mode N-factor growth, resulting in an approximate 15% downstream shift in the transition location. At higher speeds (M > 7), vibrational non-equilibrium emerges as the primary stabilization pathway for the second mode. LST calculations demonstrate that introducing a vibrational temperature (T_{vib}) gradient that peaks at the critical layer can reduce the maximum spatial growth rate of the second mode by 30% to 50%, potentially extending the transition N-factor envelope length by more than 30%. Furthermore, the investigation into active wave cancellation confirms its theoretical viability while highlighting significant practical challenges. While the underlying phase control logic is mathematically sound, the bandwidth and spatial precision required for current ns-DBD technology remain at the edge of feasibility, necessitating a careful trade-off between the energy cost of high-frequency pulsing and the achieved transition delay. Ultimately, these mechanisms are not mutually exclusive; a practical Plasma-Activated Kinetics (PAK) system would likely utilize a steady or low-frequency component for base flow conditioning and first-mode suppression, thereby creating a more favourable environment for the high-frequency active damping of the second mode.

V. CONCLUSIONS

This theoretical investigation demonstrates that Plasma-Activated Kinetics (PAK) holds significant promise for delaying transition in hypersonic flight. By strategically depositing thermal energy using ns-DBD plasma actuators, we can stabilize the boundary layer through several complementary paths: modifying the base flow, introducing stabilizing species and vibrational gradients, and employing direct anti-phase wave cancellation. Our linear stability analyses suggest that the transition Reynolds number can be increased by more than 30%, which could represent a major breakthrough in managing the intense heat loads faced by hypersonic vehicles. The most practical approach for immediate use involves steady or low-frequency pulsed heating to suppress first-mode instabilities, alongside vibrational non-equilibrium to dampen second-mode growth. While the logic behind closed-loop active wave cancellation is sound, its successful implementation remains a longer-term goal that depends on future advances in high-bandwidth actuator design and robust sensing. Moving forward, research must focus on high-fidelity direct numerical simulations (DNS) to validate these theoretical models, as well as experimental work to precisely characterize the thermal and chemical perturbations induced by ns-DBDs in high-enthalpy environments.

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REFERENCES

[1] S. P. Schneider, "Hypersonic laminar-turbulent transition on circular cones and scramjet forebodies," Prog. Aerosp. Sci., vol. 40, no. 1-2, pp. 1–50, Jan. 2004, doi: 10.1016/j.paerosci.2003.11.001.

[2] T. C. Corke, C. L. Enloe, and S. P. Wilkinson, "Dielectric barrier discharge plasma actuators for flow control," Annu. Rev. Fluid Mech., vol. 42, pp. 505–529, Jan. 2010, doi: 10.1146/annurev-fluid-121108-145550.

[3] D. V. Roupassov, A. A. Nikipelov, M. M. Nudnova, and A. Y. Starikovskii, "Flow separation control by plasma actuator with nanosecond pulsed-periodic discharge," AIAA J., vol. 47, no. 1, pp. 168–185, Jan. 2009, doi: 10.2514/1.38113.

[4] L. M. Mack, "Boundary-layer linear stability theory," AGARD, Neuilly-sur-Seine, France, Rep. AGARD-R-709, pp. 3-1–3-81, 1984.

[5] N. P. Bitter and J. E. Shepherd, "Stability of highly cooled hypervelocity boundary layers," J. Fluid Mech., vol. 778, pp. 586–620, Sep. 2015, doi: 10.1017/jfm.2015.421.

[6] A. V. Fedorov, "Transition and stability of high-speed boundary layers," Annu. Rev. Fluid Mech., vol. 43, pp. 79–95, Jan. 2011, doi: 10.1146/annurev-fluid-122109-160750.

[7] M. Nishihara, N. Jiang, J. W. Rich, and W. R. Lempert, "Development of nanosecond pulse driven dielectric barrier discharge plasma actuators for active flow control," in Proc. 41st AIAA Fluid Dyn. Conf. Exhib., Honolulu, HI, USA, 2011, Art. no. 2011-4870, doi: 10.2514/6.2011-4870.

[8] C. L. Chang and M. R. Malik, "Oblique-mode breakdown and secondary instability in supersonic boundary layers," J. Fluid Mech., vol. 273, pp. 323–360, Jun. 1994, doi: 10.1017/S002211209400194X.

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