



Thermomechanical Relaxation of Vibrationally Excited NO in a Hypersonic Turbulent Boundary Layer

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Motivation

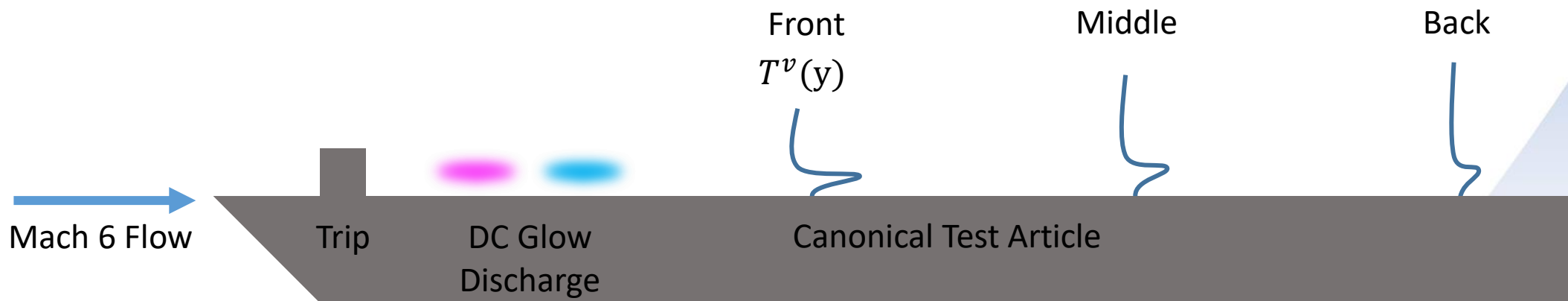
Experimental Setup

Results

Conclusion

Vibrational and Turbulent Coupling

- Extend theory to hypersonic environment
- Create a two-temperature flow in with canonical turbulence
- Collect validation data
- Build problem successively
 1. Laminar, no plasma: No TKE, no TNE
 2. Turbulent, no plasma: TKE, no TNE
 3. Laminar/Turbulent, plasma: TKE, TNE





Motivation

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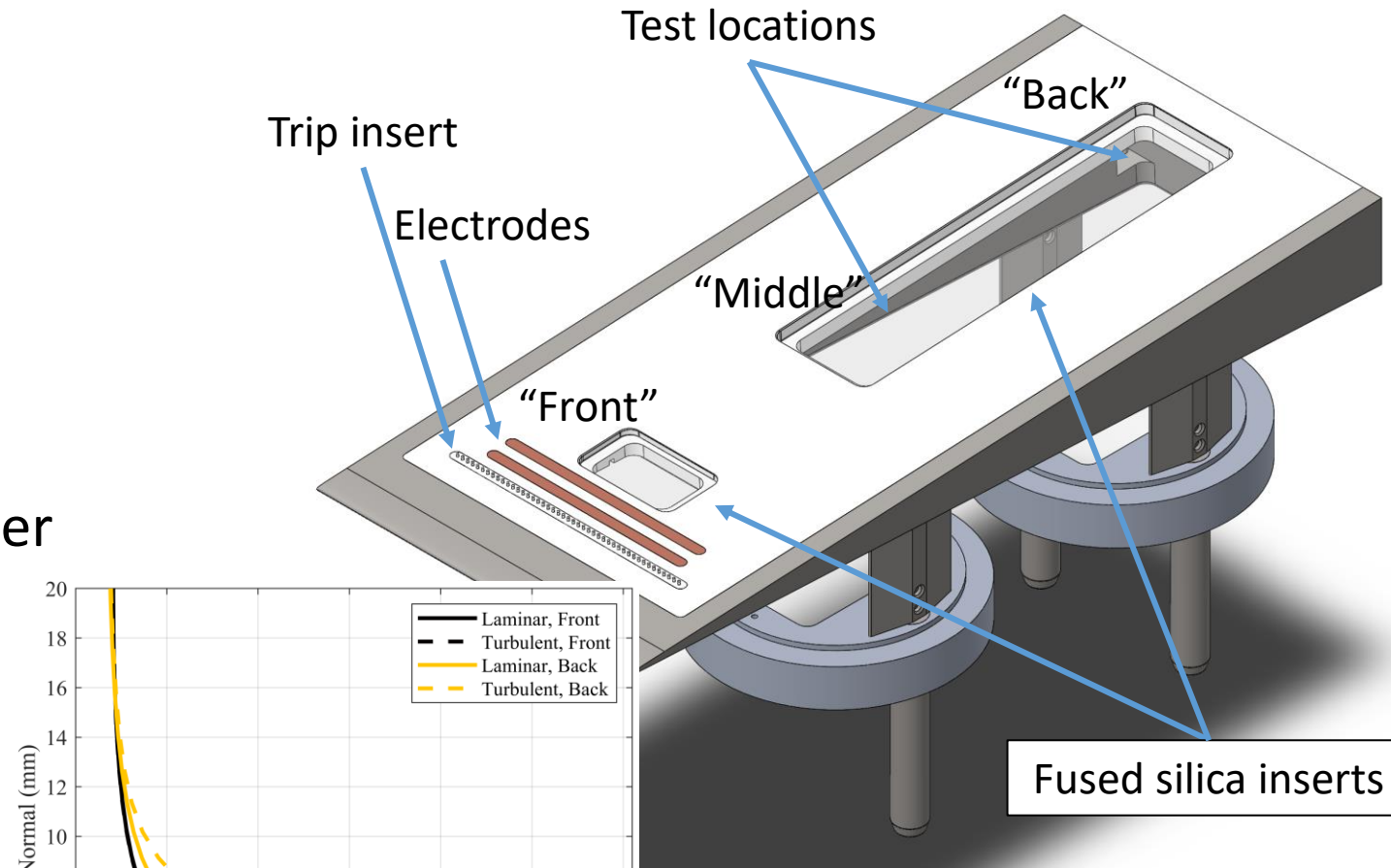
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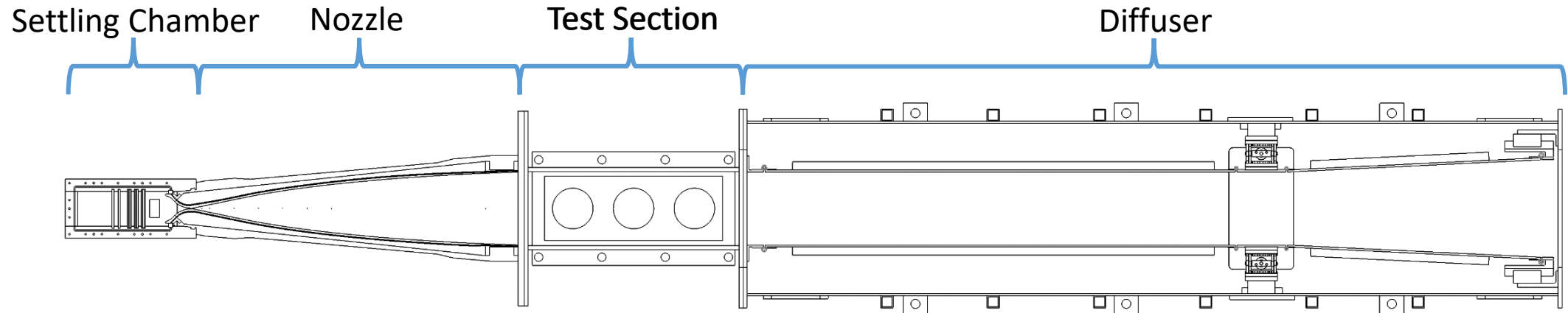
Experimental Setup



- Canonical 2.75° half-angle wedge
 - Diamond trip insert scaled with BL
 $[h, w, s] = [1.5, 2, 4] \delta_{99.5\%, Ho}$
 - Electrodes produce ~ 47 W DC glow discharge
 - Polynomial-defined LE ($R_{eff} = 0.318\text{mm}$)
- US3D simulations of T^r boundary layer
 - Modified Steger-Warming inviscid flux, DPLR implicit time integration
 - $150 \times 420 \times 1$ nodes
 - $Y^+ < 1$, 1.5x global refinement
 - Spalart-Allmaras RANS model



Actively Controlled Expansion (ACE) Tunnel



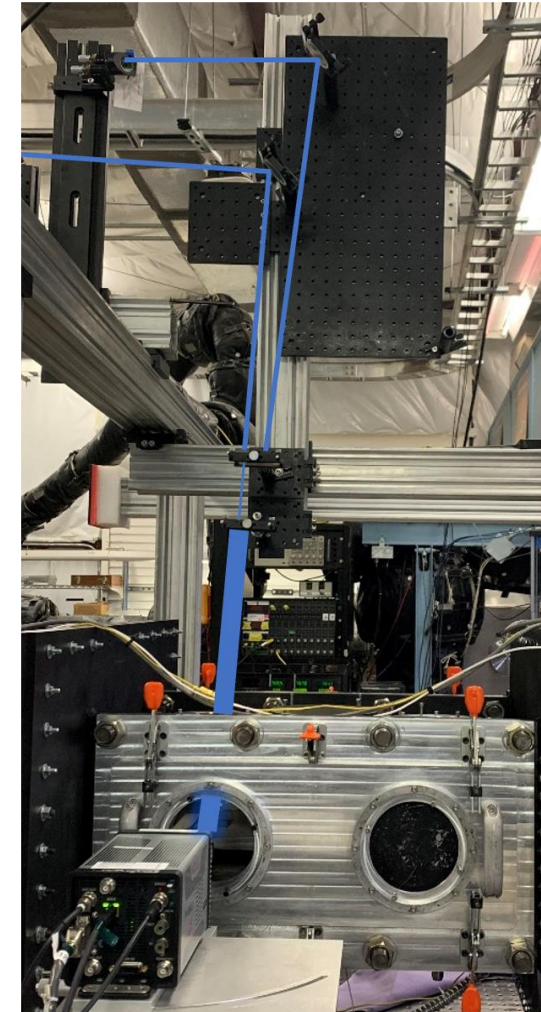
M	Re ($10^6/m$)	P_o (kPa)	T_o (K)	P (Torr)	T (K)	ρ (kg/m^3)	$\frac{P'_{RMS}}{P}$ (%)
5.70 ± 0.05	6.00 ± 0.25	496.42 ± 20.68	430 ± 15	3.23 ± 0.13	57.35 ± 2.00	2.61 $\pm 2 \times 10^{-2}$	1.5 ± 0.25



NO PLIF Vibrational Thermometry



- Probed NO J 4.5 rotational state of Q₂₁/R₁ branch
 1. Excite NO $A^2 \Sigma^+(v' = 1) \leftarrow X^2 \Pi_{1/2}(v'' = 1)$
 2. ICCD 1: Collect, (100 ns gate)
 3. Delay 500 ns
 4. Excite NO $A^2 \Sigma^+(v' = 0) \leftarrow X^2 \Pi_{1/2}(v'' = 0)$
 5. ICCD 2: Collect (3 ns gate)
- ~200 frames per run, horizontally averaged into profiles
- Gas seeded in settling chamber
 - 15% NO-N₂ mix, est. 0.1683 – 0.0462% (by mass) in ROI
- Calibration and quantification
 - For Frames A and B: $R = \frac{N_{p,A}}{N_{p,B}} = C_{12} * \exp\left(-\frac{\Delta\epsilon_{AB}}{k_b T}\right)$



Picture reprinted from Broslawski (2022) with permission



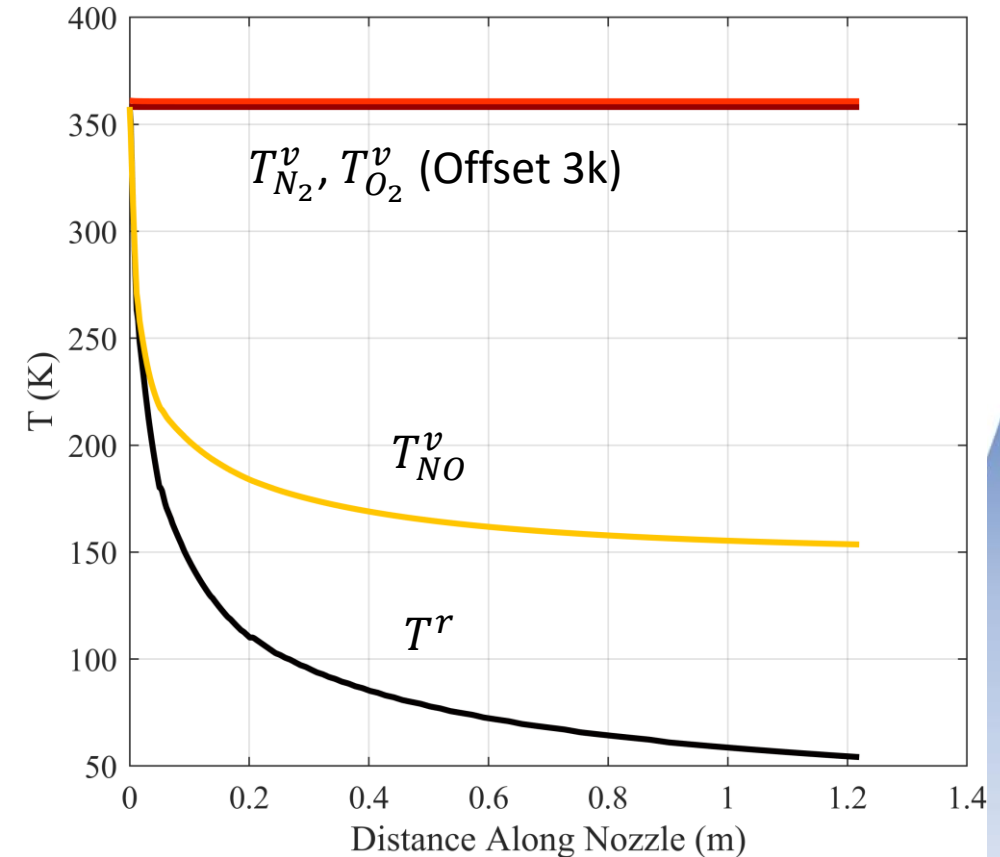
Chemical Kinetics Model



- Assume:
 - Thermal equilibrium at nozzle throat
 - Boltzmann population distribution
- Track number of vibrationally excited molecules
 - Ex. - $\frac{d[NO^{v=1}]}{dt} = -k_f[NO^{v=1}][O_2] + k_r[NO][O_2^{v=1}]'$

$N_2^{v=1} + O_2^{v=0} \leftrightarrow O_2^{v=1} + N_2^{v=0}$
$N_2^{v=1} + NO^{v=0} \leftrightarrow NO^{v=1} + N_2^{v=0}$
$NO^{v=1} + O_2^{v=0} \leftrightarrow O_2^{v=1} + NO^{v=0}$
$N_2^{v=1} + (N_2, O_2, NO)^{v=0} \leftrightarrow N_2^{v=0} + (N_2, O_2, NO)^{v=0}$
$O_2^{v=1} + (N_2, O_2, NO)^{v=0} \leftrightarrow O_2^{v=0} + (N_2, O_2, NO)^{v=0}$
$NO^{v=1} + (N_2, O_2, NO)^{v=0} \leftrightarrow NO^{v=0} + (N_2, O_2, NO)^{v=0}$

- T_m^v calculated from Boltzmann distribution
 - $T_m^v = -\Delta E_m^v / (k_b \ln[N_m^{v=1} / (N_m^{v=0} + N_m^{v=1})])$





Motivation

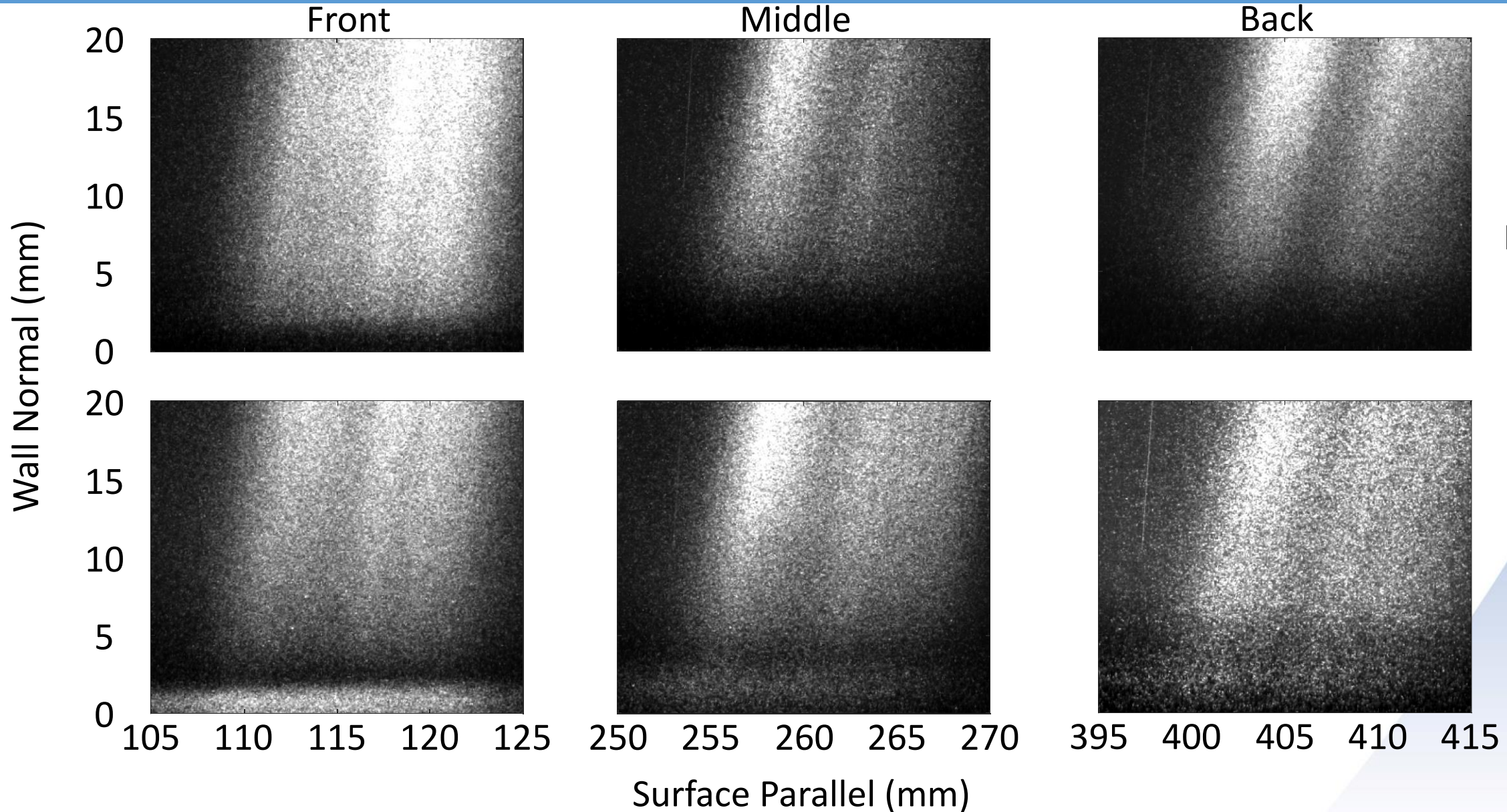
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Raw PLIF Data: Laminar

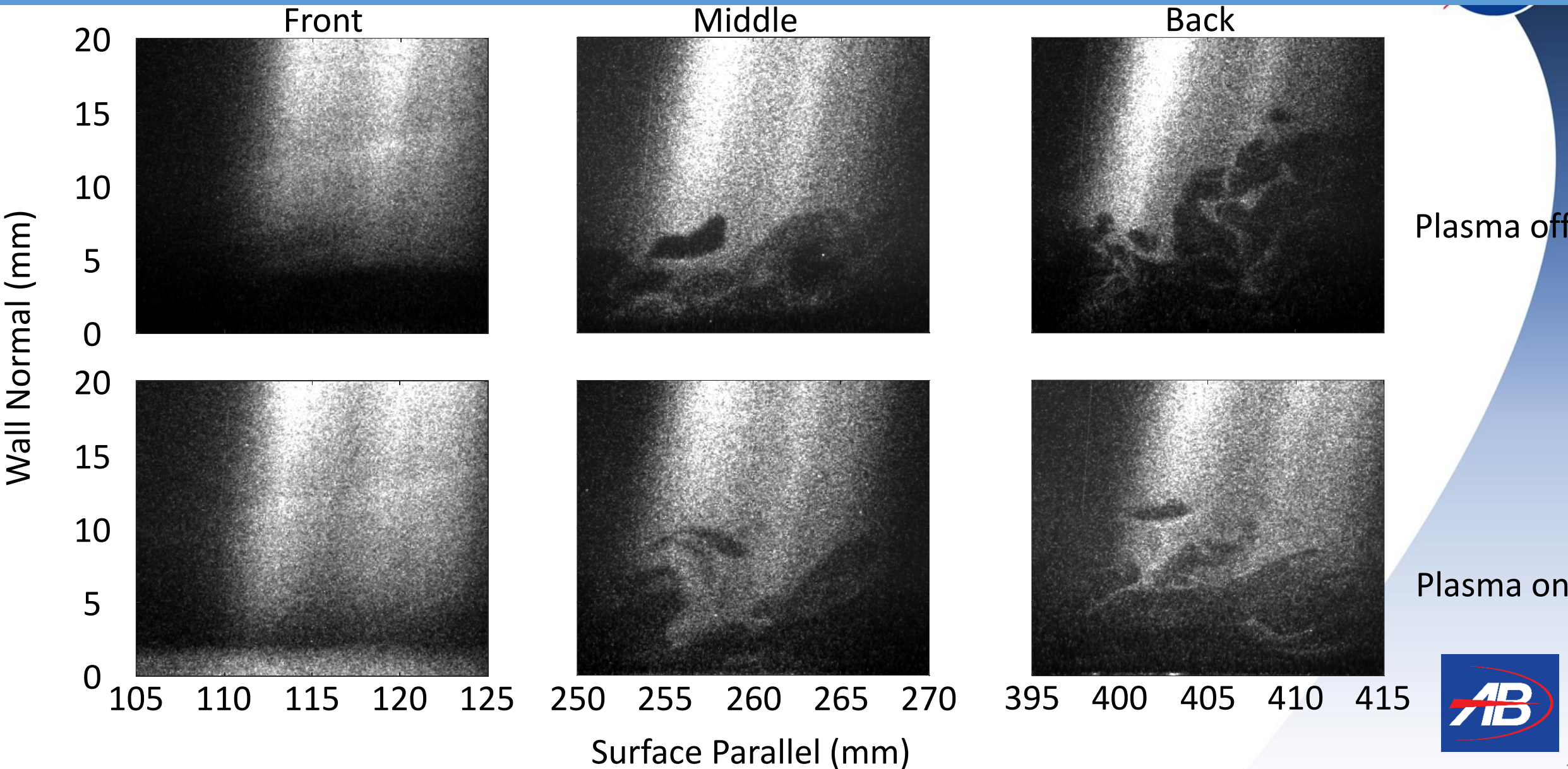


Plasma off

Plasma on

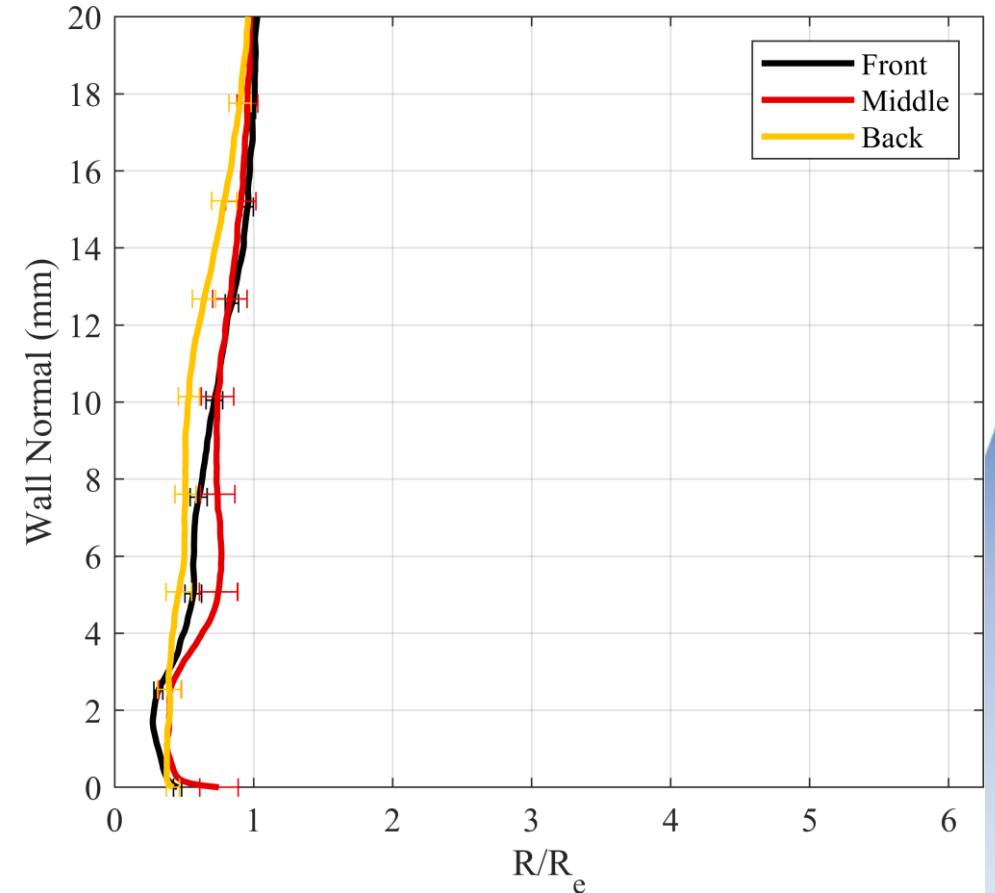


Raw PLIF Data: Laminar



Laminar Baseline Case

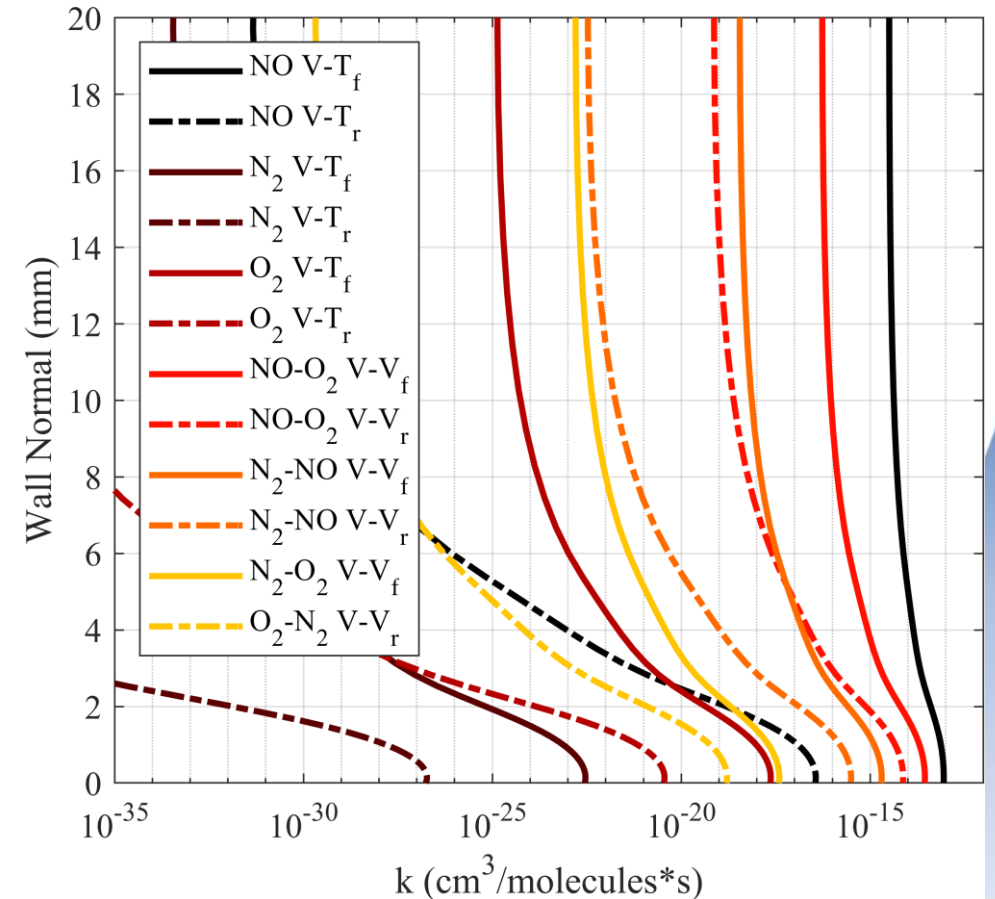
- Little evolution along plate, small rise
- Freestream profile due to
 - Gradient in tunnel
 - Presence of N_xO_y species
- Deficit near wall due to
 - Thermodynamics (to be discussed)
 - Entropy layer effects
- If $T_w \approx 358K > T_{e,NO}^v = 153.7K$, why is $\left(\frac{R}{Re}\right)_e \geq \left(\frac{R}{Re}\right)_w$?
 - $R \propto T$
 - Poor simulation of $T_{e,NO}^v$
 - Vibrational slip



System Thermodynamics



- Thermodynamics “turn on” on hot BL
- Three dominant reactions
 1. Collisional self-quenching of $NO^{v=1}$
 2. $NO^{v=1} \rightarrow O_2^{v=1}$
 3. $NO^{v=1} \leftarrow O_2^{v=1}$
- Est. 100x more O_2 than NO
 - $T_{O_2}^v > T_{NO}^v$
 - $\theta_{v,O_2} < \theta_{v,NO}$
 - Similar trend for $N_2^{v=1} \rightarrow NO^{v=1}$
- Explains slight rise in BL vibrational temperature



Introduce Turbulent Mixing

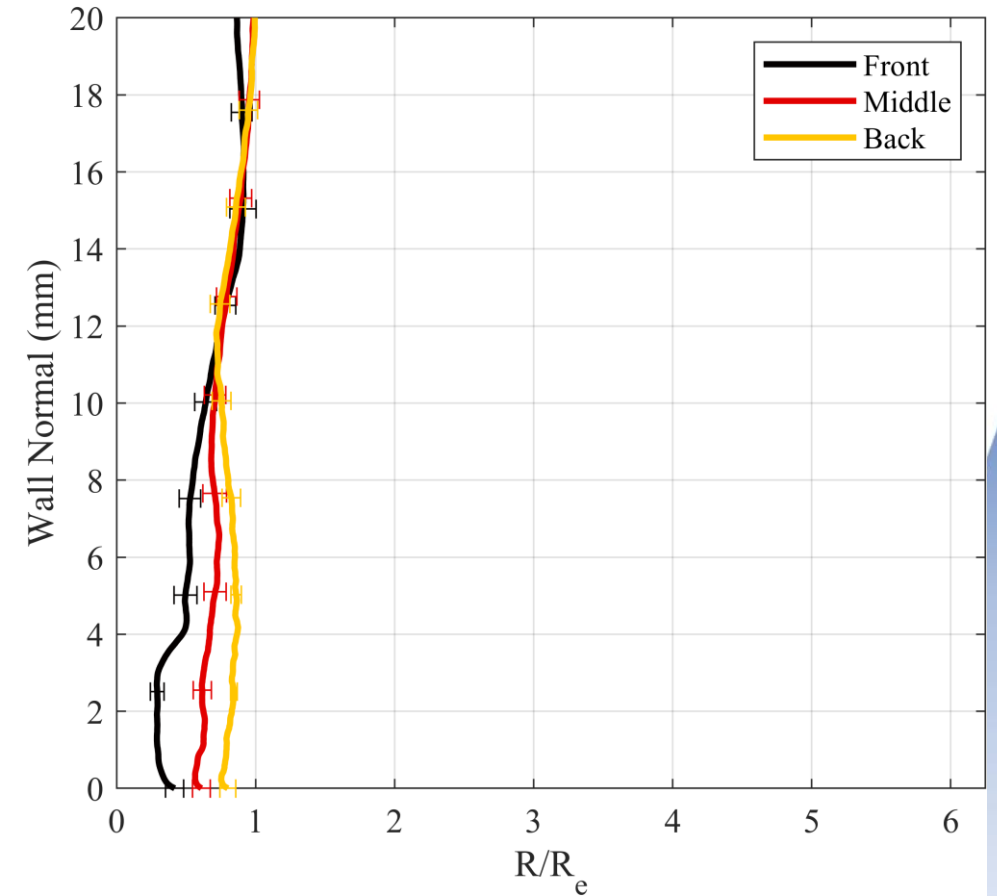
- Trips added mixing to convection & diffusion
- Deficit at “Front” fully homogenized

- Implies $\tau_{turb} < \tau_{vib}$

- Timescales:

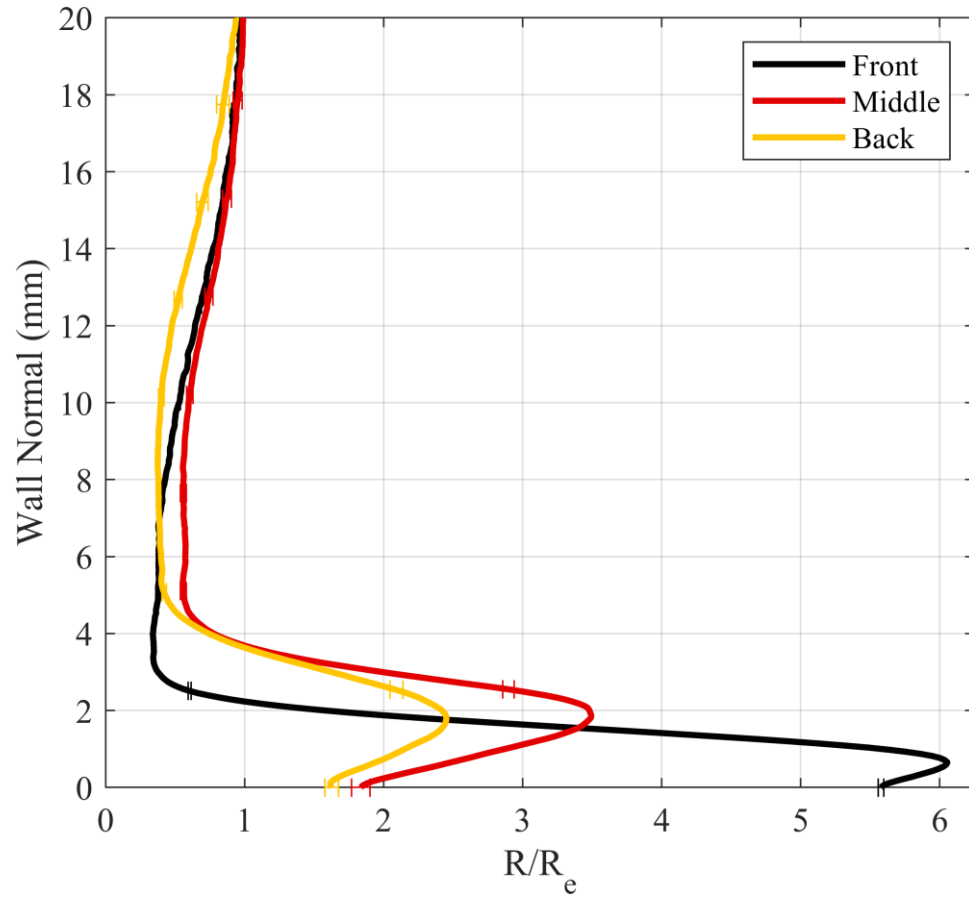
- Landau-Teller: $\tau_{LT} = (N_m k_f [1 - \exp(-\theta_v/T)])^{-1}$
 - Only models V-T self-quenching
 - Flow: $\tau_F = l_{body} / u_e$
 - Large-scale eddy turnover: $\tau_E = \delta / u_e$
 - Kolmogorov: $\tau_\eta \approx \nu / \epsilon$
 - Taylor microscale: $\tau_\lambda \approx \frac{\lambda}{(K^T)^{1/2}} \approx \sqrt{10} \tau_\eta$

- Vibrational relaxation **can** occur on flow/turbulence timescales

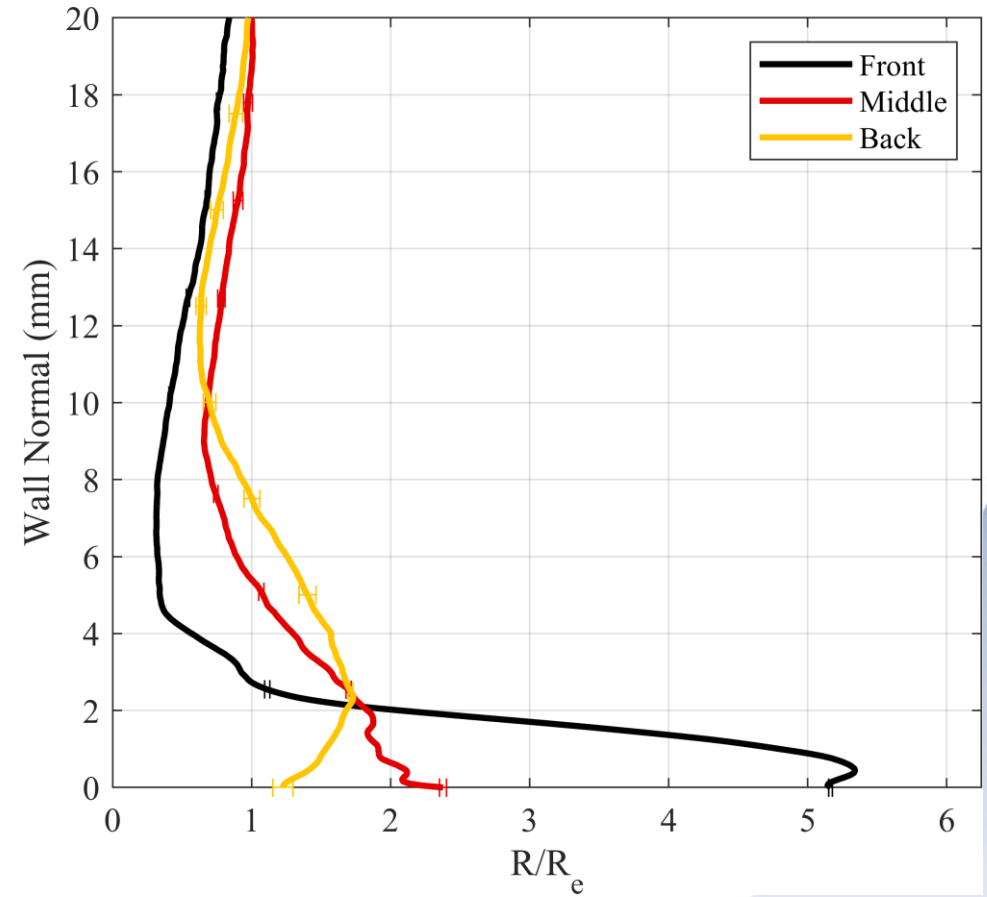


$\tau_{LT, NO}$	τ_F	τ_E	τ_η	τ_λ
$< 1 \times 10^{-4}$	$> 5 \times 10^{-4}$	1×10^{-5}	5×10^{-6}	1×10^{-5}

Introduce Thermal Nonequilibrium



Laminar



Turbulent





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- Successfully excited NO in a cold hypersonic tunnel
 - Simplified physics to aid analysis
- Applied low-fidelity approach to relaxation modeling
- Quasivibrational temperature data collected
 - First known application of PLIF to boundary layer vibrational thermometry
 - Better calibration technique needed
 - Results provided at “Inlet” and two “Test” locations
- Incremental experiment applied
 - Laminar, no plasma: Identified likely relaxation pathways
 - Turbulent, no plasma: Showed $\tau_{turb} \approx \tau_v$
 - Turbulent, plasma: Regions of dominant physics
 - Near wall: Thermodynamics
 - Far wall: Fluid mechanics



Thank you!



References



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