Effect of Gas Injection on Transition in Hypervelocity Boundary Layers

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A novel method to delay transition in hypervelocity flows in air over slender bodies by injecting CO₂ into the boundary layer is presented. The dominant transition mechanism in hypersonic flow is the inviscid second (Mack) mode, which is associated with acoustic disturbances which are trapped and amplified inside the boundary layer [8]. In dissociated CO₂-rich flows, nonequilibrium molecular vibration damps the acoustic instability, and for the high-temperature, high-pressure conditions associated with hypervelocity flows, the effect is most pronounced in the frequency bands amplified by the second mode [3].

Experimental data were obtained in Caltech’s T5 reflected shock tunnel. The experimental model was a 5 degree half-angle sharp cone instrumented with 80 thermocouples, providing heat transfer measurements from which transition locations were from turbulent intermittency based upon laminar and turbulent heat flux correlations. An appropriate injector was designed and fabricated, and the efficacy of injecting CO₂ in delaying transition was gauged at various mass flow rates, and compared with both no injection and chemically inert Argon injection cases. Argon was chosen for its similar density to CO₂. At an enthalpy of approximately 10 MJ/kg (Eckert’s reference temperature $T_e = 2550$ K), transition delays in terms of Reynolds number were documented. For Argon injection cases at similar mass flow rates, transition is promoted.
Effect of gas injection on transition in hypervelocity boundary layers

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PROBLEM: In hypersonic flight, heating loads are typically a dominant design factor

*Turboulent heat transfer rates can be about an order of magnitude higher than laminar rates at hypersonic Mach numbers*

A reduction in heating loads by keeping the boundary layer laminar longer means less thermal protection needed and hence less weight to carry, or conversely more payload deliverable for a given thrust.

OBJECTIVE: Delay transition from laminar to turbulent flow in the boundary layer of a slender hypersonic body by using nonequilibrium CO$_2$

Transition in high Mach numbers occurs through the Mack mode – amplification of acoustic waves traveling in the boundary layer

Molecular vibration and dissociation damp acoustic waves

At relevant conditions, CO$_2$ absorbs most energy at the frequencies most strongly amplified by 2$^{nd}$ (Mack) mode

*Inject CO$_2$ to delay transition in air flows of interest*
Background

- Experimental data show that transition is delayed for CO$_2$ flows compared with N$_2$ and air flows for a given stagnation enthalpy, $h_0$
- These observations point to a second mode transition (or Mack mode) for the conditions studied as well as to the importance of non-equilibrium effects of CO$_2$ on stabilizing the flow


CO$_2$ Transition Re* is about 5X that of Air and N$_2$
Background

Computations show that when pure CO\textsubscript{2} is in vibrational and chemical non-equilibrium, these relaxation processes absorb energy from acoustic disturbances in the boundary layer whose growth is responsible for transition in hypervelocity flows.

Confirms trends seen in experiments where CO\textsubscript{2} exhibits delayed transition with respect to Air or N\textsubscript{2} for \( h_0 \sim 5-10 \text{MJ/kg} \).


For air – no effect from vibrational relaxation and chemical reactions on stabilizing the boundary layer.

For CO\textsubscript{2} – vibrational relaxation and chemical reactions stabilizes the boundary layer.
Background

- Computed acoustic absorption rates (open symbols) – Fujii et. al
- Computed acoustic amplification rates (solid symbols) – after Reshotko/Beckwith and Mack
- For CO₂ the broad sound absorption curve peak coincides with the amplification peaks
- This coincidence is most pronounced at enthalpies of ~10 MJ/kg

Facility: T5 Hypervelocity Shock Tunnel

Impulse Facility, test time in the order of ms, but high stagnation enthalpies and pressures
Free-stream mixtures with CO$_2$

Porous Injector

Porous Injector Rationale

- Move to a transpiration-like approach instead of discrete jets
- High velocity jets disturbed the boundary layer – penetrate to shock layer
- Need lower flow penetration into the boundary layer
- Can achieve same flow rates as with jets ~ 0-50 g/s

Porous injector section
Sintered 316LL Stainless Steel
10 μm media grade
Porous Injector Results (10 MJ/kg)

10-micron Porous Injector (Ar injection at 3.7 grams/sec)

Average over test time

(1.500 – 2.100 ms)
Porous Injector Results (10 MJ/kg)

10-micron Porous Injector (no injection)

Heatflux distribution - Shot #2598

Time = 1.000 ms

Average over test time

(1.500 – 2.100 ms)
Porous Injector Results (10 MJ/kg)

10-micron Porous Injector (CO$_2$ injection at 3.7 grams/sec)

Average over test time

(1.500 – 2.100 ms)
Porous Injector Results 1/2

Re vs. injection @ ~10 MJ/kg, ~55 MPa
Data reduction: Average Heat Transfer Method

No injection: porous section

Argon Injection: 3.7 g/s

CO2 injection: 3.7 g/s
Data Reduction: Intermittency Method

Turbulent intermittency


Alternate method to determine transition location
Porous Injector Results (10 MJ/kg)

Re vs. injection @ ~10 MJ/kg, ~55 MPa

Summary of results (intermittency method)
Theoretical Injection

- Free-stream gas is Nitrogen
- Different injection geometry
  - 5 degree cone, transpiration from 10 to 90 cm on the cone
  - Injection based on profile suggested by Malik*
    - $\dot{m}$ based on edge conditions and parameter, $f_w$
      - For these cases, $f_w$ held constant
        - Mass flux decreases down the length of the cone

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<th>Stagnation Conditions</th>
<th>Free-stream Conditions</th>
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<td>Velocity (m/s)</td>
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Computational Results

- Transition occurs at $N = \sim 9.2$
- Significant transition delay vs. smooth cone for CO2
- Air and N2 injection both promote transition
- Mass flux = 2.5 grams/sec (but over entire surface; “Malik cone”)
- Smooth cone, $x_{tr} = 63$ cm

From Wagnild et al 2010
Computational Results

- Transition delay predicted
  - Increase in CO₂ initially results in further delay but further increase causes more amplification
- For $N_{cr} = 9.2$
  - Smooth cone, $x_{tr} = 63$ cm, $f_w = 0.1$, $x_{tr} = 72$ cm
- For $N_{cr} = 9.2$
  - Smooth cone, $x_{tr} = 63$ cm
  - $f_w = 0.1$, $x_{tr} = 83$ cm

- Pre-heating further delays transition
  - CO₂ able to absorb acoustic energy earlier
  - Higher temperature gas could also contribute

From Wagnild et al 2010
Effect of gas and Temperature on Transition Delay: CFD predictions

Alternate gases only increase disturbance

CFD predicts that for the current porous design and longer porous injectors transition could be delayed for optimum flow rates and temperature of CO₂
• Aerospace America 2009 – Year in Review: Fluid Mechanics
  “AFRL, Caltech, and the University of Minnesota have collaborated in a numerical and experimental study on control of high-speed boundary layers. The team has demonstrated significant delays in transition”

• Annual Reviews of Fluid Mechanics 2011, 43:79-95. – Federov, A.
  “Transition and Stability of High-Speed Boundary Layers”:

  “..Another way to stabilize the second mode and thereby delay transition is to add CO2 into high enthalpy boundary-layer flow (Leyva et al. 2009). The motivation for this new technique lies in the following findings: Molecular vibration and dissociation suppress the acoustic instability, and at relevant conditions for hypersonic flight, CO2 absorbs energy most strongly in the frequency band associated with the second mode.

  The experiments of Leyva et al. (2009) on a sharp slender cone in the GALCIT T5 tunnel showed that the CO2/N2 free-stream blends (without injection) lead to significant delay of transition. The transition Reynolds number more than doubled for mixtures with 40% CO2 mole fraction compared with the case of 100% N2. A similar effect was noted in experiments using mixtures of air and CO2 as the test gas. Experimental and numerical studies of the CO2 injection system suitable for this LFC concept are in progress. The effect of the injection and the transition location is gauged by solving the PSEs and using the semiempirical $eN$ method (Wagnild et al. 2010)..”
Half-Porous/Half-Smooth Injector

Plot of St vs Reₜ for T5-2656: P₀ = 78.4 MPa, h₀ = 7.59 MJ/kg, T₀ = 5128.1 K

Plot of St vs Reₜ for T5-2657: P₀ = 78.3 MPa, h₀ = 8.6 MJ/kg, T₀ = 5577.5 K

Plot of St vs Reₜ for T5-2658: P₀ = 64.8 MPa, h₀ = 8 MJ/kg, T₀ = 5278.9 K

Distribution A: Approved for public release; distribution unlimited
## Boundary Layer Temperatures

<table>
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<tr>
<th>$H_0$ (MJ/kg)</th>
<th>$P_0$ (MPa)</th>
<th>$T^*$ (Eckert)</th>
<th>$T_{edge}$</th>
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<td>5.69 – 5.92</td>
<td>~ 30</td>
<td>1465 K</td>
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<td>1395 K</td>
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<td>9.46 – 10.32</td>
<td>~55</td>
<td>2725 K</td>
<td>1728 K</td>
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</table>

Latest →
Ongoing Challenges

10.3 MJ/kg, 55 MPa
Natural transition @ 72 cm
Delay observed

8.6 MJ/kg, 78 MPa
Natural transition @ 54 cm
Delay NOT observed

- In both cases, $T^*$ and $T_e$ are above the critical 960K for CO$_2$
- Why is delay not observed for injection in the case on the right?

Distribution A: Approved for public release; distribution unlimited
Ongoing Challenges

Possible Explanation

• N-factor at transition is similar (5.0-5.6 for a noisy tunnel) in both cases
• N-factor at the injector section location (13.3 cm from the tip) is therefore significantly higher for the case with earlier natural transition (right hand plot on previous slide)
• To suppress the 2nd mode, mixing must be achieved at a relatively low (but not precisely known) N-factor

Variables to optimize for attaining delay by injecting CO₂

• N-factor at injection location
• \( \frac{(T^* \text{ or } T_e \text{ of boundary layer base flow})}{(T_{vib} \text{ of CO}_2)} \)
• \( \frac{(\text{mixing distance for CO}_2 \text{ with boundary layer base flow})}{(\text{cone length})} \)
• \( \frac{(\text{CO}_2 \text{ mass flow rate})}{(\text{boundary layer base mass flow})} \)

Collaboration with Alexander Fedorov – Moscow Inst of Physics and Tech

• Determine how low the N-factor at injection must be, and where this physically occurs on the cone
• Redesign of injector section to move it closer to the tip, achieving injection before the 2nd mode acoustic waves appear
Conclusions

• At 10 MJ/kg enthalpy, demonstrated delay versus Argon injection and also versus a smooth injector
  – CO₂ does make a difference!

• Selected a new condition at about 8-9 MJ/kg for further study
  – Meant to show a greater effect because natural transition occurs near the middle of the cone
  – However, CO₂ injection did NOT seem to delay transition at this condition

• Designed and installed a half-porous, half-smooth porous injector
  – Provides a non-injection “control” with every injection experiment

• Collaboration with Alexander Federov to for theoretical/computational input into injector design and placement
Questions ?
Back up
Preliminary results from resonantly enhanced field focused schlieren system (REFFSS)
Preliminary results from resonantly enhanced field focused schlieren system (REFFSS)

~900 microns

Thermocouple
Preliminary results from resonantly enhanced field focused schlieren system (REFFSS)
Preliminary results from REFFSS

RMS Response vs. Time - Shot 2644

\[ h_R = 6 \text{ MJ/kg} ; \ p_R = 50 \text{ MPa} \]
Preliminary results from REFFSS

RMS Response vs. Time - Shot 2647

h_R = 6 MJ/kg ; p_R = 30 MPa
Heated Carbon Dioxide

- Baseline condition similar to shot 2541
  - Test gas is air
  - Free-stream Mach is 5.3
  - Isothermal wall at 293 K
- Pre-heated CO₂
  - Momentum of injection matched with 13.5 g/s of cold carbon dioxide
- Increase in heating results in decreased amplification
  - Reduction in amplification more efficient near 1000 K

<table>
<thead>
<tr>
<th>Stagnation Conditions</th>
<th>Free-stream Conditions</th>
</tr>
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<tbody>
<tr>
<td>Pressure (MPa)</td>
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<tr>
<td>Entalpy (MJ/kg)</td>
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<tr>
<td>Density (kg/m³)</td>
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<td>Temperature (K)</td>
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<tr>
<td>Velocity (m/s)</td>
<td>3957.9</td>
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</table>
Computational Model

• Computations done using STABL software suite
  — Mean flow
    • 2\textsuperscript{nd} order accurate fluxes
    • Modified Steger-Warming
    • 1\textsuperscript{st} order Implicit DPLR method for time integration
    • Finite rate chemistry and T-V energy exchange
  — Disturbances
    • STABL PSE-chem solves the parabolized stability equations
    • PSE predict amplification of disturbances
    • Finite rate chemistry and T-V energy exchange
    • Semi-empirical e\textsuperscript{N} method used for determining transition location
Transition Determination Uncertainty

Plot of St vs Reᵋ for TS-2589; P₀ = 56.3 MPa, h₀ = 10.37 MJ/kg, T₀ = 6251.7 K

- Experimental
- Laminar
- Van Driest II
- White & Christoph
Porous Injector Results: Intermittency Method

Re vs. injection @ ~10 MJ/kg, ~55 MPa

- CO2
- Argon
- Smooth
Data Reduction: Intermittency Method

Turbulent intermittency

Transition location determined from intersection
Data Reduction: Intermittency Method

Turbulent intermittency

Transition location determined from intersection
Porous Injector Results (10 MJ/kg)

10-micron Porous Injector (Ar injection at 11.6 grams/sec)

Transitional flow

\[ \text{Re}_{tr} = 2.88 \times 10^6 \]
Porous Injector Results (10 MJ/kg)

10-micron Porous Injector (no injection)

Plot of St vs Re_x for T5-2598; P_0 = 55.3 MPa, h_0 = 10.26 MJ/kg, T_0 = 6204 K

- **Experimental**
- **Laminar**
- **Van Driest II**
- **White & Christoph**

Initially laminar flow

Re_tr = 4.12 x 10^6
Porous Injector Results (10 MJ/kg)

10-micron Porous Injector (CO$_2$ injection at 11.6 grams/sec)

**Completely laminar flow**

$\text{Re}_{tr} \geq 5.22 \times 10^6$
Porous Injector Results (10 MJ/kg)

Summary of results (average heat transfer method)

- CO₂ (Porous Injector)
- Smooth
- Argon (Porous Injector)
Porous Injector Results (10 MJ/kg)

Re vs. injection @ ~10 MJ/kg, ~55 MPa

Two porous control shots
Porous Injector Results (10 MJ/kg)

Re vs. injection @ ~10 MJ/kg, ~55 MPa

Five smooth control shots
Porous Injector Results (6 MJ/kg)

Porous tip – no injection vacuum plenum

CO₂ injection 4 g/s

Injection of CO₂ and argon destabilize boundary layer and transition occurs earlier at lower enthalpy/temperature.

Ar injection 4 g/s
Qualitative visualization

Before shot

Injection into vacuum

Porous Injector with cone downstream and 80 psi injection

Shot 2539
Po = 52 MPa
ho=9.7 MJ/kg

Schlieren seems to capture the CO2 injection clearly
Porous Injector Results

**CO₂ injection at 18.5 g/s**

Immediately turbulent flow (streak due to injector flaw)

**CO₂ injection at 26.6 g/s**
**CFD test conditions**

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<tr>
<th>Gas Composition (by mass fraction)</th>
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<td>N2</td>
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</tr>
<tr>
<td>N</td>
</tr>
<tr>
<td>O</td>
</tr>
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</table>
Why vibration relaxation and dissociation damp acoustic waves


- Following Clarke and McChesney, the linearization of perturbations of the N-S equations leads to damping curve as shown – Maximum damping occurs when $\omega \tau = a_f/a_e$

- Relaxation processes such as molecular vibration and dissociation cause damping of acoustic waves through *phase lag between pressure and density*
First injector models

<table>
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<tr>
<th>Model No.</th>
<th>Hole diameter, d (mm)</th>
<th>No. Rows</th>
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**Injector Variants**

**Model No. 1**

- Four injectors designed and built
REFERENCES


### Vibrational temperatures

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<th>species</th>
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<th>$h_J^2$ (J/mol)</th>
<th>$g_J$</th>
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Dissociation temperatures

\[ \text{St} = \frac{q}{\rho e u_e} \left( h_0 - 0.5u_e^2 (1 - r) - C_p T_w \right) \]

Air, \( \rho = 0.01 \text{kg/m}^3 \)

CO₂, \( \rho = 0.01 \text{kg/m}^3 \)

\( \text{N}_2 \), \( \rho = 0.01 \text{kg/m}^3 \)

\( \text{N}_2 \), \( \rho = 0.10 \text{kg/m}^3 \)
### Table A.1: Summary of freestream conditions for all shots.

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Preliminary Results with Porous Injector

Control Experiment – Smooth Surface

Porous injector design looks very promising

Porous Injector – no flow

Boundary layer not disturbed

Preliminary data with porous injector and 20 psi CO2 run tank pressure

Boundary layer not disturbed
The injection of CO₂ is triggered by a proximity switch sensing the recoil of T5, ~100 ms before flow begins in the test section.
Experimental model

Injector section installed in ~1m long, 5-degree half angle cone
Preliminary Results (10 MJ/kg)

Control Experiment – Smooth Surface

Initially laminar flow

$\text{Re}_{tr} = 4.36 \times 10^6$
Four rows of orifices

Injector with four rows of orifices, installed in T5 test section
Preliminary Results

Four-Row Injector (CO2 injection at 26.0 grams/sec)

Plot of $St$ vs $Re_x$ for T5-2529: $P_0 = 48.9$ MPa, $h_0 = 10.22$ MJ/kg, $T_0 = 6150$ K

- Experimental
- Laminar
- Van Driest II
- White & Christoph

Immediate Transition

Heat Flux Distribution - Shot #2529

Cone surface coordinate (m)

Heat Flux (MW/m²)
Preliminary Results

Four-Row Injector (no injection)

Immediate Transition
One row injector

One row of orifices
Preliminary Results

One-Row Injector (no injection)

Transition (though not immediately full turbulence)
T profile and N factor for high and low enthalpy conditions

For $P_0=30\text{MPa}$, $h_0=5.7\ \text{MJ/kg}$ (shot 2582)

For $P_0=54\text{MPa}$, $h_0=10\ \text{MJ/kg}$ (shot 2569)

$T$: solid line
$M$: dash dot line
N2 results

Gas inj into N2 @ ~10 MJ/kg, ~50 MPa
Porous Injector Results (10 MJ/kg)

Summary of results (intermittency method)
Porous Injector Results 1/2

Re vs. injection @ ~10 MJ/kg, ~55 MPa

Transition Reynolds Number

2.50E+06

3.00E+06

3.50E+06

4.00E+06

4.50E+06

5.00E+06

5.50E+06

mass flux (g/s)

0

5

10

15

20

- CO2
- Argon
- Smooth