Computational Analysis of High Enthalpy Effects on 2nd Mode Disturbances

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This effort is focused on using linear stability analysis (PSE) and Navier-Stokes solvers to study the effect of non-equilibrium effects, present in high-enthalpy flows, on 2nd mode disturbances and transition. The effort is concentrated on flows over slender cones with air, CO₂, and mixtures of those two gases as the test gases.
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Introduction

- Transition on slender, constant-angle cones
- Fujii and Hornung
  - Investigated acoustic damping in equilibrium mixtures
- Jewell et al.
  - Porous injection of $\text{CO}_2$ into a hypervelocity boundary layer on a sharp cone

Amplification and absorption over a range of frequencies in $\text{CO}_2$
Previous work

• Modeling T5 shock tunnel experiments
  – 5° half-angle sharp cone
  – Smooth and injection inserts
  – Air, N₂, and CO₂
  – $h_0 \sim 4 - 10.5\, MJ/kg$
  – $P_{res} \sim 30 - 85\, MPa$

Test cone used in T5 tunnel experiments
Computational Tools

• Tunnel Flow
  – Nozzle Code + STABL CFD solver
    • 2D and axi-symmetric, reacting Navier-Stokes
    • Second-order accurate fluxes
    • High-pressure, excluded-volume equation of state
  – US3D
    • Solves 3D, reacting Navier-Stokes Equations
    • Inviscid fluxes are formulated for low dissipation
    • Viscous fluxes are second-order accurate
    • Implicit time advancement up to second-order accurate
    • High-pressure, excluded-volume equation of state

• Stability Analysis
  – PSE-Chem
    • Solves the axi-symmetric linear PSE
    • Includes finite-rate chemistry and T-V energy exchange
Current Efforts:

• Freestream Mixtures
  – Air + CO₂
• Prediction Goals
  – Large transition delay in T5
  – Ensure effective application of damping
    • “Freezing” vibration in PSE stability analysis
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Change in transition location due to vibrational damping
Current Efforts

- **Experiments**
  - Measured clear distinction in $\text{Re}_\text{tr}^*$
  - Observed transition delay

\[
\frac{T^*}{T_e} = \frac{1}{2} + \frac{\gamma - 1}{2} \frac{\sqrt{\text{Pr}}}{6} M_e^2 + \frac{1}{2} \frac{T_w}{T_e}
\]

\[
\text{Re}_\text{tr}^* = \frac{\rho^* u_e x_{\text{tr}}}{\mu^*}
\]

*Transition Reynolds number from experiments*
Current Efforts

• Computational Analysis
  – Decrease in amplification with increase of CO$_2$
  – Consistent $N_{tr} \sim 10$
    • Range of freestream compositions
    • Range of Enthalpy

Computed max N factor for various T5 experiments
Current Efforts

• Computational Analysis
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Computed transition N factor* for various T5 experiments

*Error Bars indicate ± 4 cm.
Future Interests

• Apply this computational method to other high-enthalpy facilities
  – Do we see the same trends?
    • Gain confidence in modeling tools
    • Opportunity to improve modeling deficiencies

• Open to other high-enthalpy transition research
Questions/Comments?

• Referenced Papers:

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Vibrational Relaxation Effects on Acoustic Disturbances

- **Geometry**
  - $7^\circ$ half-angle sharp cone
  - Nose radius $12.5 \ \mu m$
  - Length $0.5 \ m$

- **Conditions**
  - $h_0 = 4.6 \ M J/kg$
  - $Re = 2.6 \times 10^7 \ 1/m$
  - $Mach = 12.58$

Contours of density disturbance for the $1.4 \ MHz$, slow wave case