Thermodynamic characterization of supersonic expansions using shadowgraphy and numerical Simulations

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Who we are and what brings me here

- MEMS (Micro Electronic Mechanical Systems) research lab in Argentina
- Sensors, actuators, e-noses, RF switches.
- Now: micronozzles
Motivation

• Molecular beams, condensation
• Cheap, quick way to analyze nozzle flow
  – Flow rate, species concentrations
  – Temperature, Pressure, etc.
• Options:
  – Interferometry
  – Schlieren
  – Shadowgraphy
Mach Diamonds

Underexpansion

http://www.aerospaceweb.org/question/propulsion/q0224.shtml
Shadowgraphy

- Simplest optical setup imaginable
- Index change at Mach Diamonds
- Intensity

\[ I(n) \propto \frac{\partial^2 n}{\partial x^2} \]

Sample Images
Information in shadowgrams

- Separation of Mach Barrels
- Processing in ImageJ
CFD in ANSYS Fluent

- Implicit density-based solver
- SST $k-\omega$ turbulence method
- 2-3 steps of mesh adaption
- Meshes smaller than 20,000 cells
- Convergence in less than 10000 iterations
Converged solution in Fluent

Density
Temperature
Mach
Pressure
Image Comparison

Shadowgrams

Simulations
Simulations in both cases, diamond positions “fall off”
Drop-off for the peak positions

Attributed to viscous losses in the literature
Mass Flow

1-D Theory

\[ F = \rho u A = \rho^* v_s^* A^* \]

\[ T^* = \left( \frac{2}{\gamma + 1} \right) T_{in} \]

\[ \rho^* = \left( \frac{2}{\gamma + 1} \right) \frac{1}{\gamma - 1} \rho_{in} \]

\[ p^* = \left( \frac{2}{\gamma + 1} \right) \frac{\gamma}{\gamma - 1} p_{in} \]

\[ F(p_{in}) = \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \frac{\gamma A}{v_{s,in}} p_{in} \]

\[ F_{1D} \approx 0.776 F_{sim} \]

Summary

• Supersonic jet characterization by:
  – Extreme experimental simplicity
  – “Simple enough” simulations

• Good for:
  – Quick and dirty assessment
  – Classroom assignments

• Next steps:
  – Improve pictures (Schlieren)
  – Other fluid characterization (interferometry, pressure-sensitive paints, PIV, etc.)
  – Transient flow