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APPLICATION OF CFD CODES FOR THE SIMULATION OF SCRAMJET COMBUSTOR FLOWFIELDS

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ABSTRACT

An overview of CFD activities in the Hypersonic Propulsion Branch is given. Elliptic and PNS codes that are being used for the simulation of hydrogen-air combusting flowfields for scramjet applications are discussed. Results of the computer codes are shown in comparison with those of the experiments where applicable. Two classes of experiments will be presented: (a) parallel injection of hydrogen into vitiated supersonic air flow; and (b) normal injection of hydrogen into supersonic crossflow of vitiated air.

INTRODUCTION

- A number of CFD codes are being developed and validated at the Hypersonic Propulsion Branch, Fluid Mechanics Division, NASA Langley Research Center
- These CFD codes are being applied to solving flowfields inside hydrogen-fueled scramjet combustors
- Fully elliptic codes
  - 2D, Axisymmetric, 3D
  - Global two-step finite rate combustion model
  - Use unsplit explicit MacCormack Algorithm with point-implicit chemistry source terms
- PNS Codes
  - 2D, 3D
  - Global two-step finite rate combustion model
  - Implicit, coupled space marching procedure

3D-ELLIPTIC CFD CODE

- Unsplit explicit MacCormack finite-difference algorithm
- Solve 9 PDE's by finite-difference technique
  - 1 Density
  - 3 Momentum
  - 1 Energy
  - 4 Species (O_2, H_2, H_2O, OH)
- Treat chemical source terms implicitly to alleviate stiffness associated with fast chemistry
- 2D-Layer design for efficient use of memory

COMBUSTION AND TURBULENCE MODELS

- Four-species two-step finite-rate model (Rogers-Chinitz)

$$H_2 + O_2 \underset{kb1}{\overset{kf1}{\rightleftharpoons}} 2OH$$

$$2OH + H_2 \underset{kb2}{\overset{kf2}{\rightleftharpoons}} 2H_2O$$

kf, kb = kf, kb (ϕ ,T)

- Chemical source terms are obtained by applying the law of mass action
- Prandtl mixing length hypothesis for the jet mixing process

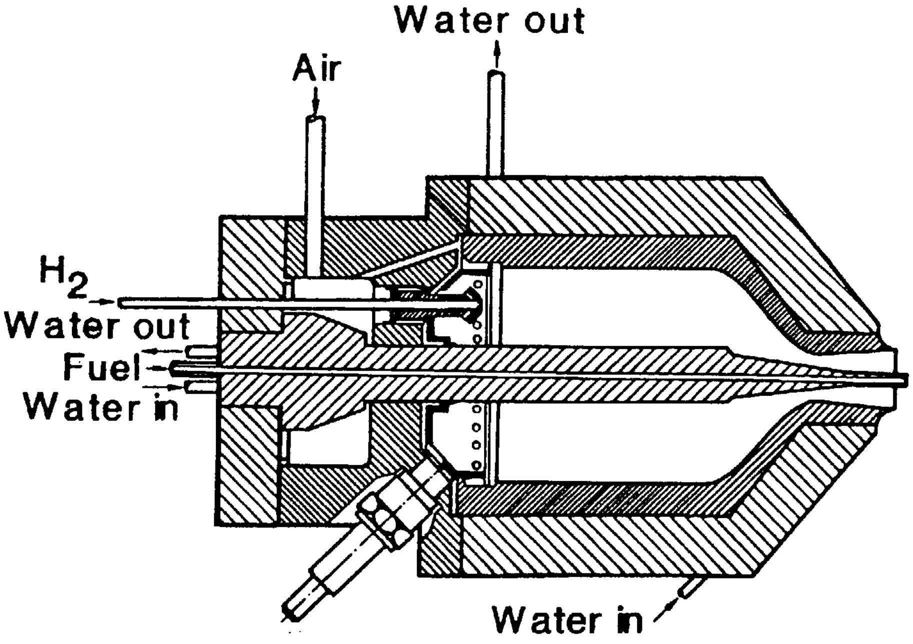
$$\mu_t = k\rho\omega\ell^2$$

$$k \approx 0.02$$

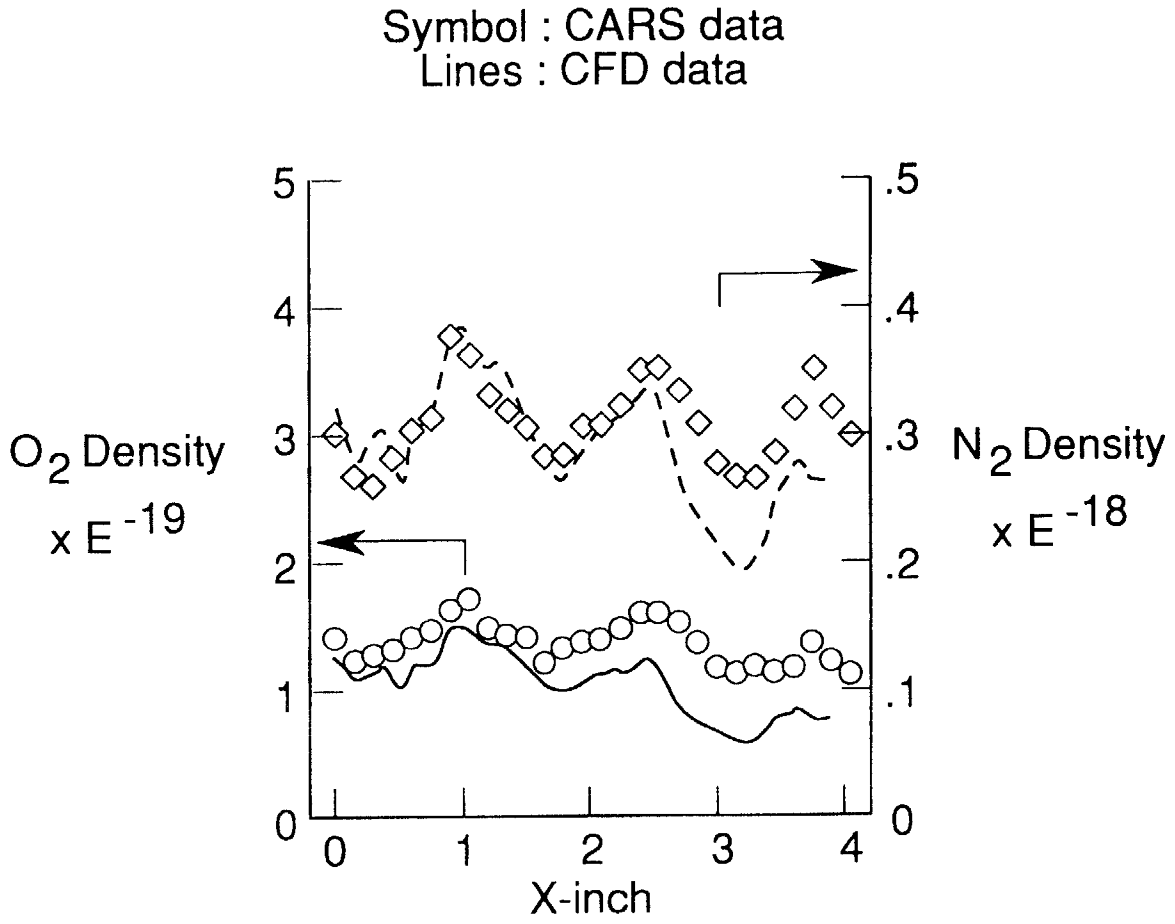
- Baldwin-Lomax model for near-wall turbulence

RESULTS OF 2D ELLIPTIC CODE

- Supersonic coaxial burner of hydrogen-air
- Hot vitiated outer air stream co-flowing with cold inner hydrogen fuel, exiting into a quiescent air
- Use "CARS" technique to obtain data point for oxygen, nitrogen and temperature
- Compare CARS data with CFD results



CENTERLINE DISTRIBUTION OF O_2 AND N_2 SPECIES

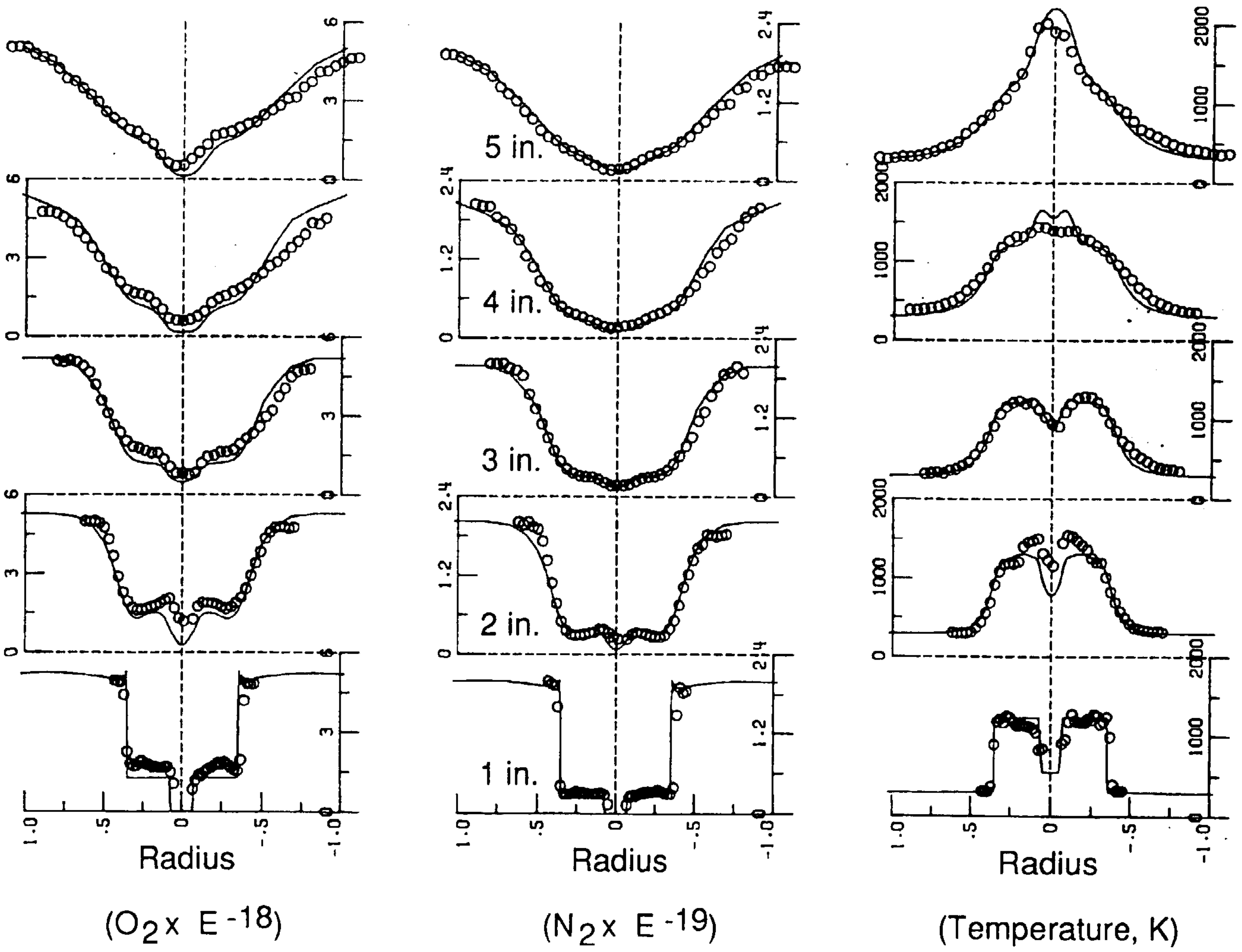


- Wavy distributions due to shock waves reflection from the free stream
- Flame was, infact, ignited by shock wave

RESULTS OF 2D ELLIPTIC CODE (CON'T)

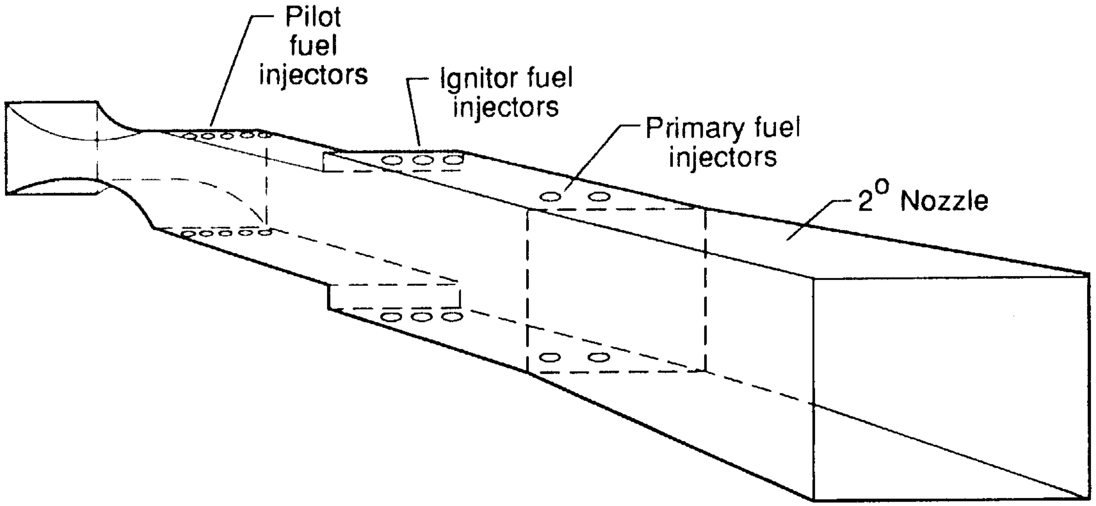
Comparison of radial distributions at various streamwise stations

○ CARS —— CFD



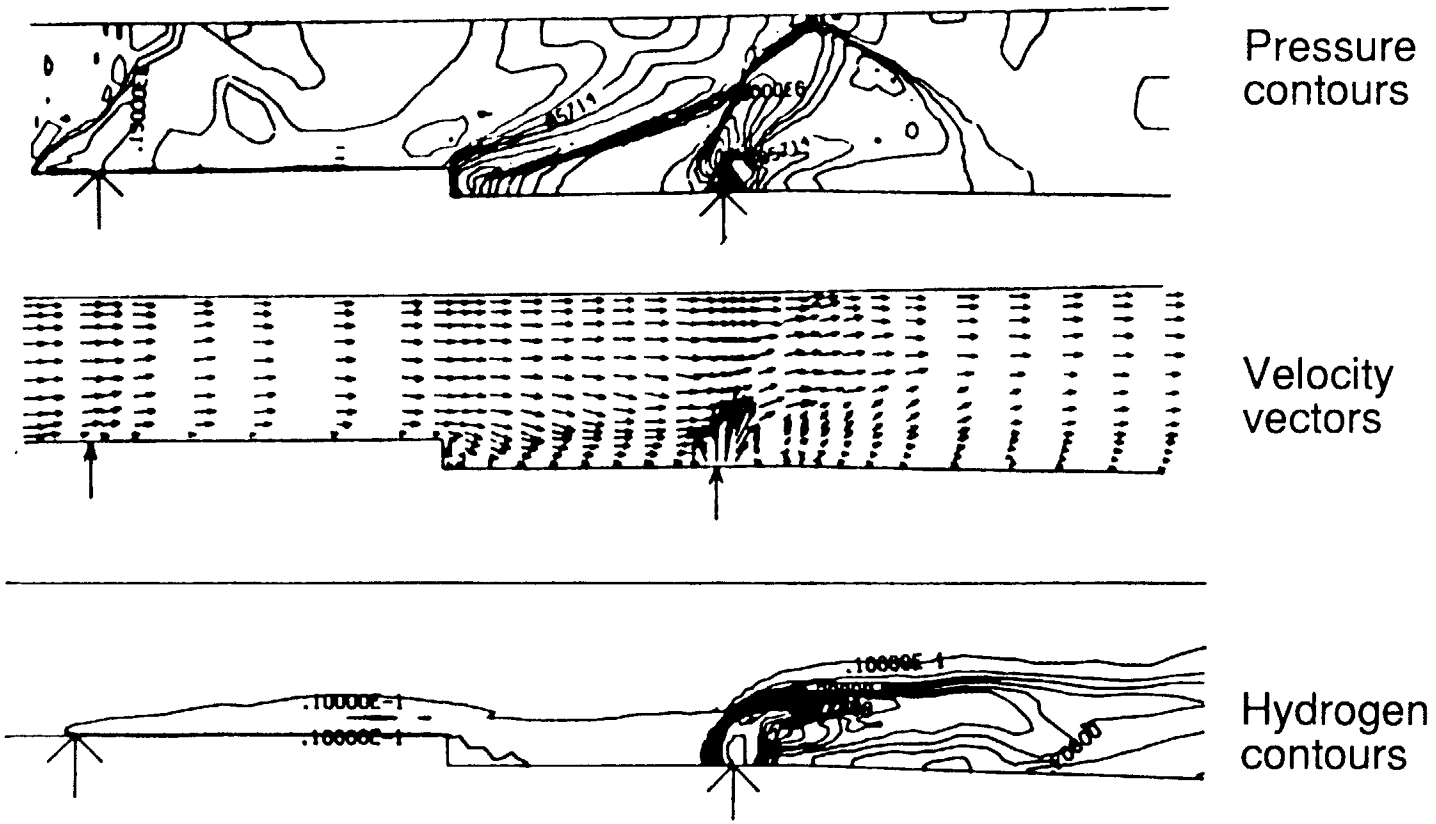
3D-CODE VALIDATION EXPERIMENT

- Subscale scramjet combustor (3.5"W, 4"L, 1.8"H) with :
  - Backward facing steps
  - Normal injections of H_2 pilot fuel, Silane ignitor fuel and H_2 primary fuel
  - 2^{o} , Nozzle (4 ft long)
- Inflow gas was Mach 2 vitiated air at high enthalpy.
- Static pressures were measured at various points along the surfaces



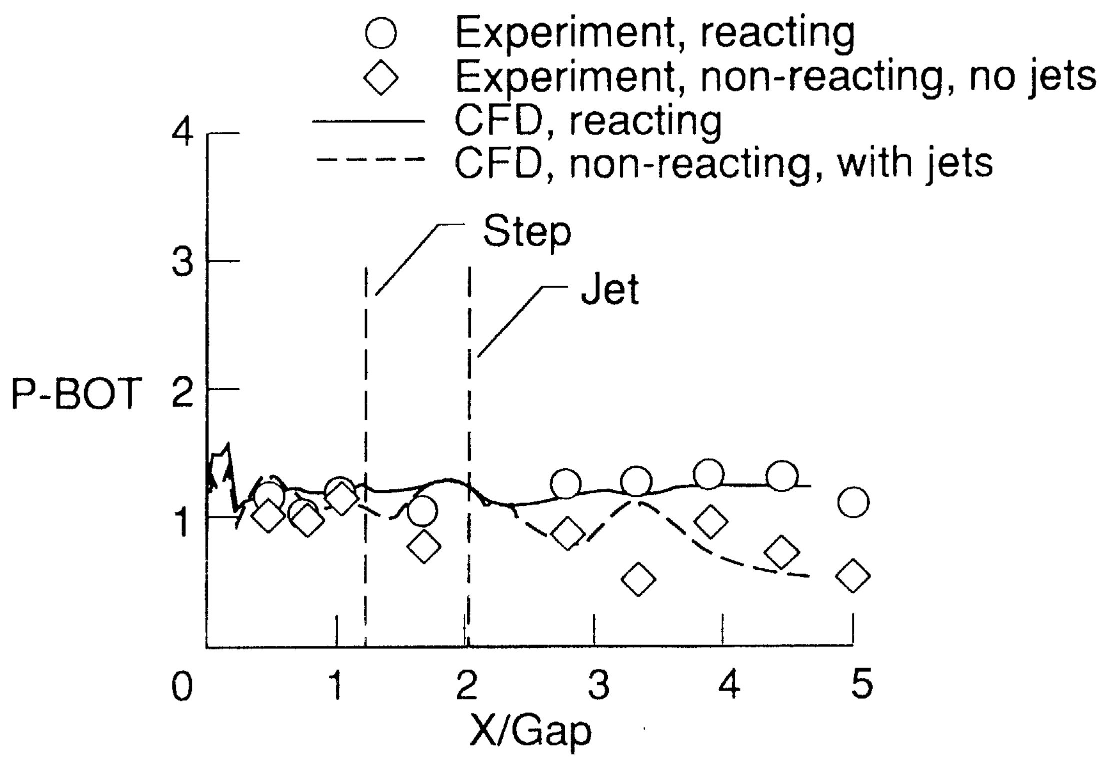
CONTOURS AND VECTORS PLOT THROUGH THE MAIN JET: NO COMBUSTION

Flow conditions: T_S = 810K, P_S = 1 atm, M = 2; ϕ = 0.43



PRESSURE DISTRIBUTIONS ALONG BOTTOM WALL AT MIDPLANE

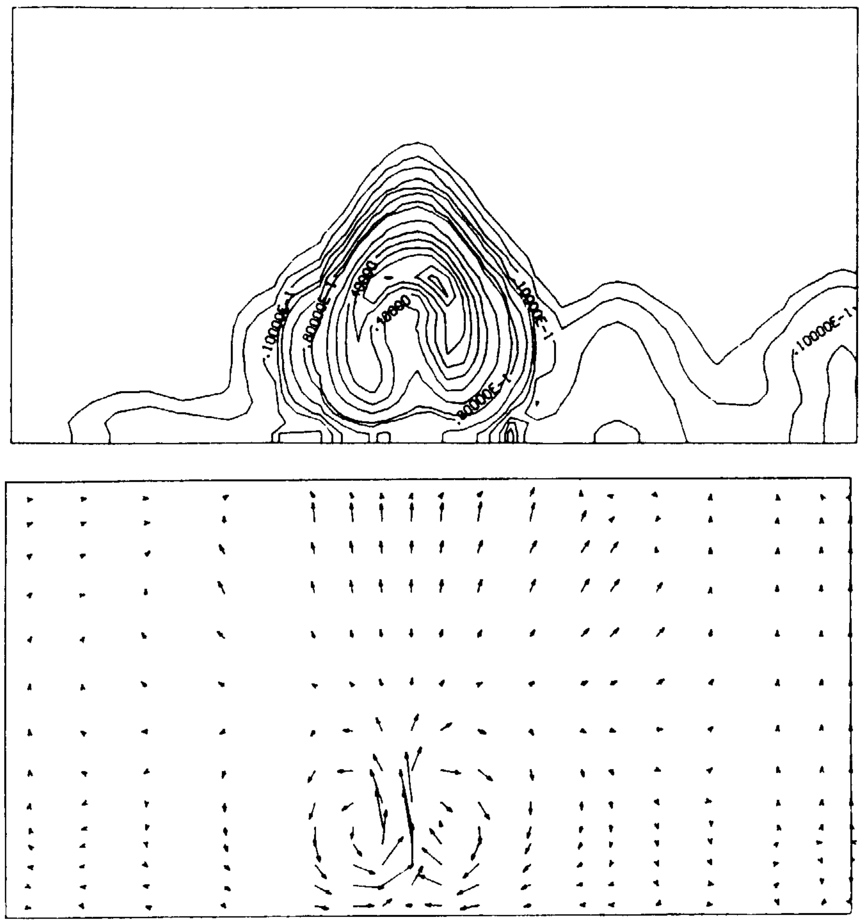
Flow conditions: $T_S = 1200K$, $P_S = 1$ atm, $M = 2$; $\phi = 0.48$



- Mixing and combustion efficiency at exit was underpredicted by 20%
- Prandtl mixing length hypothesis seems to work well

HYDROGEN CONTOURS AND VELOCITY VECTORS AT X = 1.5" DOWNSTREAM OF MAIN JET

Flow conditions: $T_S = 1200K$, $P_S = 1$ atm, $M = 2; \phi = 0.48$

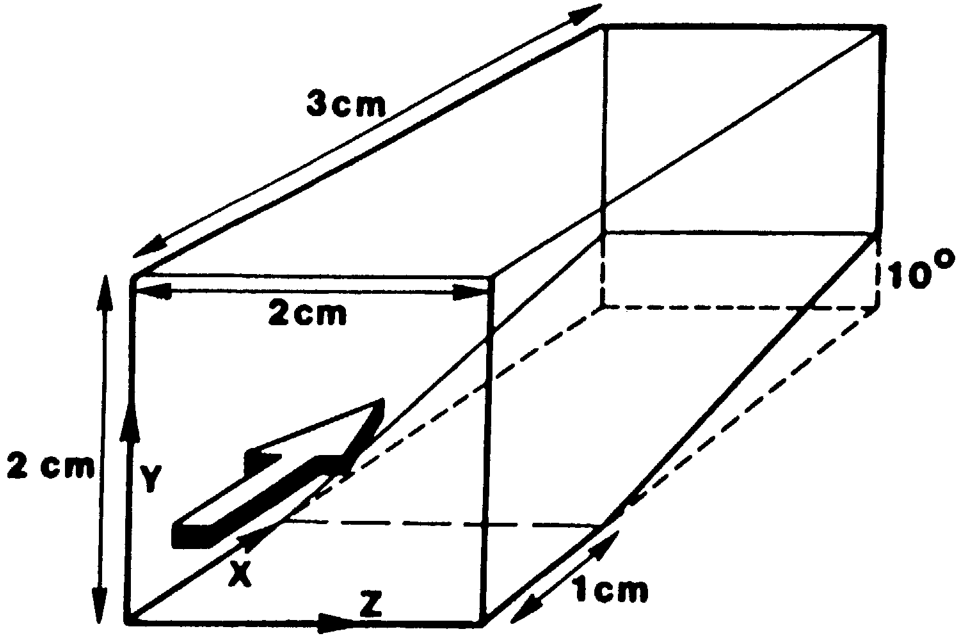


- ● Kidney shape profile
- ● Counter rotating vortices

3D-PNS CODE

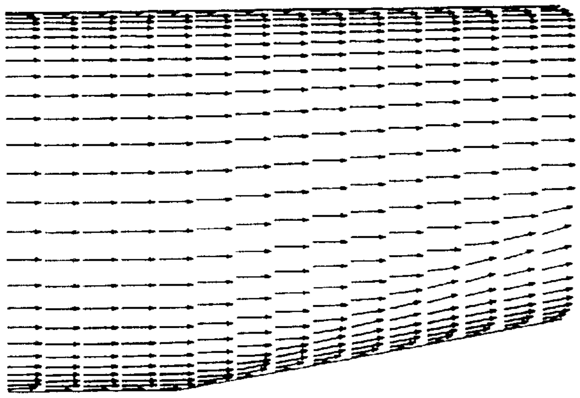
- Applicable for supersonic high Reynolds number flow
- More efficient than full Navier-Stokes procedure
- Space marching technique using steady version of beam-warming algorithm (Vigneron, et al; Schiff-Steger)
- 4 Species, 2-step combustion model (Rogers-Chinitz) for hydrogen-air
- Fluid and chemical species are solved together creating block (9 x 9) tridiagonal system
- Baldwin-Lomax turbulence model
- See also AIAA Paper 84-0438

SCHEMATIC OF THE MODEL PROBLEM FOR THE 3D-PNS CODE

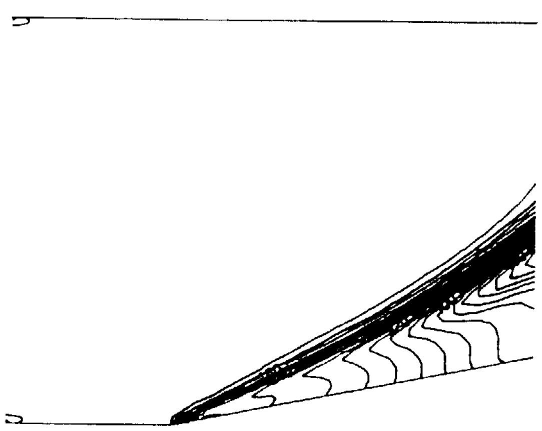


Inflow conditions: Mach = 4, T = 900K,
P = 1 atm, Equivalence ratio = 1

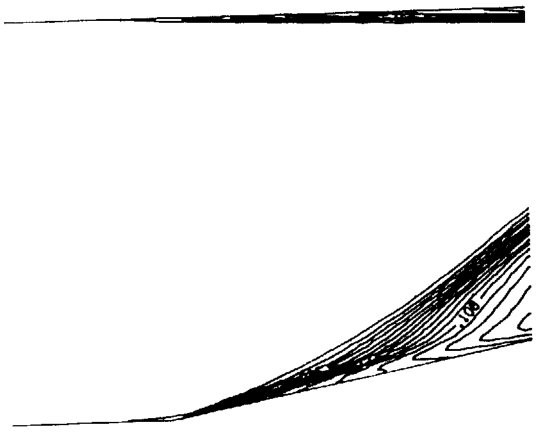
FLOW FIELD AT THE MIDPLANE



Velocity vectors



Pressure contours



Water mass fraction contours

CONCLUDING REMARKS

- Computer codes are being developed and validated at HPB, FMD, NASA-LaRC
- Results so far have shown that MacCormack algorithm, despite some drawbacks, can give good physical results
- Simple Prandtl mixing length scheme is both viable and economical
- More sophisticated combustion and turbulence models can be used at the expense of computer time which is very costly for any 3D-reacting flow simulation
- 3D-PNS code is an economical alternative to the costly elliptic code provided that certain conditions are met
- Need to make the PNS algorithm more robust