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Liquid Propellant Rocket Engine Combustion Simulation with a Time-Accurate CFD Method

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ABSTRACT

Time-accurate computational fluid dynamics (CFD) algorithms are among the basic requirements as an engineering or research tool for realistic simulations of transient combustion phenomena, such as combustion instability, transient start-up, etc., inside the rocket engine combustion chamber. A time-accurate pressure based method is employed in the FDNS code for combustion model development. This is in connection with other program development activities such as spray combustion model development and efficient finite-rate chemistry solution method implementation. In the present study, a second-order time-accurate time-marching scheme is employed. For better spatial resolutions near discontinuities (e.g. shocks, contact discontinuities), a 3rd-order accurate TVD scheme for modeling the convection terms is implemented in the FDNS code. Necessary modification to the predictor/multi-corrector solution algorithm in order to maintain time-accurate wave propagation is also investigated. Benchmark 1-D and multi-dimensional test cases, which include the classical shock tube wave propagation problems, resonant pipe test case, unsteady flow development of a blast tube test case, and H2/O2 rocket engine chamber combustion start-up transient simulation, etc., are investigated to validate and demonstrate the accuracy and robustness of the present numerical scheme and solution algorithm.

LIQUID PROPELLANT ROCKET ENGINE COMBUSTION SIMULATION WITH A TIME-ACCURATE CFD METHOD

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OVERVIEW

- BACKGROUND
- APPROACH
- NUMERICAL METHOD
- BENCHMARK VALIDATION CASES
- SUMMARY AND FUTURE PLAN

BACKGROUND

- A CONTINUING RESEARCH EFFORT TO DEVELOP A ROBUST AND ACCURATE PRESSURE-BASED CFD CODE FOR COMPLEX COMBUSTION FLOW APPLICATIONS
- HIGH-ORDER, TIME-ACCURATE AND EFFICIENT NUMERICAL SCHEMES ARE ESSENTIAL FOR TRANSIENT REACTING FLOW COMPUTATIONS
- INTEGRATION OF REALISTIC SPRAY AND REACTION MODELS FOR STEADY-STATE AND TRANSIENT FLOW APPLICATIONS IS THE FINAL GOAL

BASIC BUILDING BLOCKS

- TIME ACCURATE CFD CODES FOR ALL SPEED RANGE (FDNS, MAST, ETC.)
- GENERAL AND ROBUST TURBULENCE MODELS
  --TWO-EQUATION TURBULENCE MODELS OR HIGHER-ORDER ONES
- EFFICIENT TIME-ACCURATE FINITE-RATE CHEMISTRY SOLUTION METHODS
- REALISTIC TWO-PHASE FLOW MODELS FOR SPRAY COMBUSTION

GOVERNING EQUATIONS

- COMPRESSIBLE FLOW CONSERVATION EQUATIONS
- CONTINUITY, MOMENTUM, ENERGY (STATIC ENTHALPY) TURBULENCE MODELS AND SPECIES TRANSPORT EQUATIONS
- EDDY VISCOSITY TYPE TURBULENCE MODELING
- MULTIPLE SPECIES FORMULATION WITH FINITE-RATE CHEMISTRY
- MOMENTUM AND ENERGY EQUATIONS INCLUDE MULTIPLE PHASE SOURCE TERMS

GAS PHASE GOVERNING EQUATIONS

$$\frac{\partial \rho U}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho u_i U + \mu_e \frac{\partial U}{\partial x_i} \right) = S_U$$

where $U = \left(1, u, v, w, h, k, \varepsilon \text{ and } \alpha_n\right)$

$$S_U = \begin{cases} 0 \\ -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu_e \frac{\partial u_i}{\partial x_j}\right) - \frac{2}{3}\frac{\partial}{\partial x_j}\left(\mu_e \frac{\partial u_i}{\partial x_j}\right) + D_i + M_p u_p \\ \frac{DP}{Dt} + \Phi + Q_t + H_p + M_p\left(hv + \frac{1}{2}u_r^2\right) \\ \rho\left(P_r - \varepsilon\right) \\ \rho \frac{\varepsilon}{k}\left[\left(C_1 + C_3 P_r / \varepsilon\right) P_r - C_2 \varepsilon\right] \\ \omega_n, \quad n = 1, \ldots\ldots. N \end{cases}$$

NUMERICAL METHOD

- PRESSURE BASED FINITE DIFFERENCE NAVIER-STOKES FLOW SOLVER (BASED ON THE FDNS CODE)
- SECOND-ORDER TIME-ACCURATE (CRANK-NICHOLSON) DELTA-FORM FORMULATIONS
- CHARKRAVARTHY-OSHER THIRD-ORDER TVD FLUX LIMITER EMPLOYED FOR THE CONVECTION TERMS AS OPPOSED TO THE ORIGINAL CENTRAL PLUS ADAPTIVE DAMPING SCHEME)
- MULTIPLE-ZONE GENERAL COORDINATES MESH SYSTEMS

CHARKRAVARTHY-OSHER TVD FLUXES

$$\frac{\partial F}{\partial \xi} = f_{i+1/2} - f_{i-1/2} + h_{i+1/2} - h_{i-1/2}$$

where f and h represent first-order fluxes and TVD flux limiters respectively.

$$f_{i+1/2} = \max\left\{0, (\rho U)_{i+1/2}\right\}\phi_i + \max\left\{0, -(\rho U)_{i+1/2}\right\}\phi_{i+1}$$

$$h_{i+1/2} = \begin{cases} \frac{1}{4}|\rho U|_{i+1/2}\left\{d\phi^+_{i+1/2} + d\phi^-_{i-1/2} + \alpha\left(d\phi^+_{i+1/2} - d\phi^-_{i-1/2}\right)\right\}, U \geq 0 \\ \frac{1}{4}|\rho U|_{i+1/2}\left\{d\phi^-_{i+1/2} + d\phi^+_{i+3/2} + \alpha\left(d\phi^-_{i+1/2} - d\phi^+_{i+3/2}\right)\right\}, U < 0 \end{cases}$$

BENCHMARK VALIDATION CASES

- CLASSICAL SHOCK TUBE
  (1-D WITH 160 GRID AND 0.005 TIME STEP SIZE)
- RESONANT PIPE PRESSURE OSCILLATIONS
  (1-D WITH 100 GRID AND 0.005 TIME STEP SIZE)
- A BLAST TUBE FLOW FIELD SIMULATION
  (2-D WITH 7000 GRID AND 0.01 TIME STEP SIZE)
- A H2/O2 ROCKET ENGINE CHAMBER START-UP TRANSIENT SIMULATION
  (2-D WITH 6000 GRID AND 0.0001 TIME STEP SIZE OR 0.1 μsec)

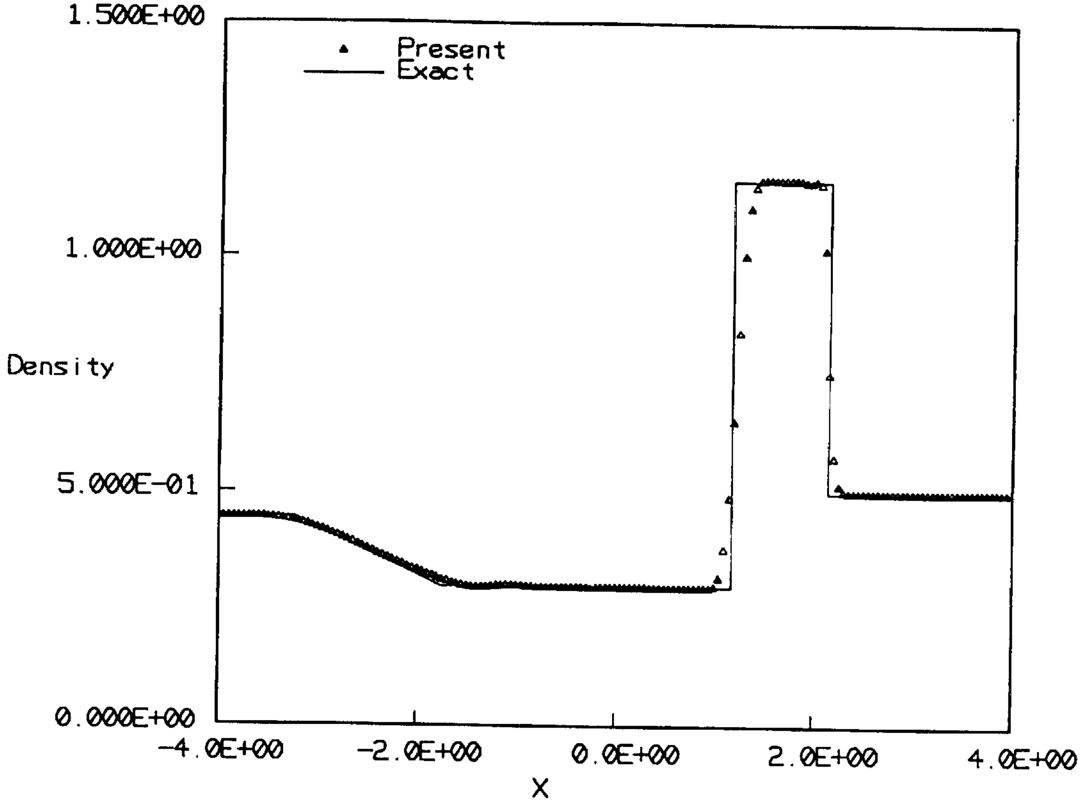

Figure 1 (a). Closed shock tube test case. (t = 0.95)

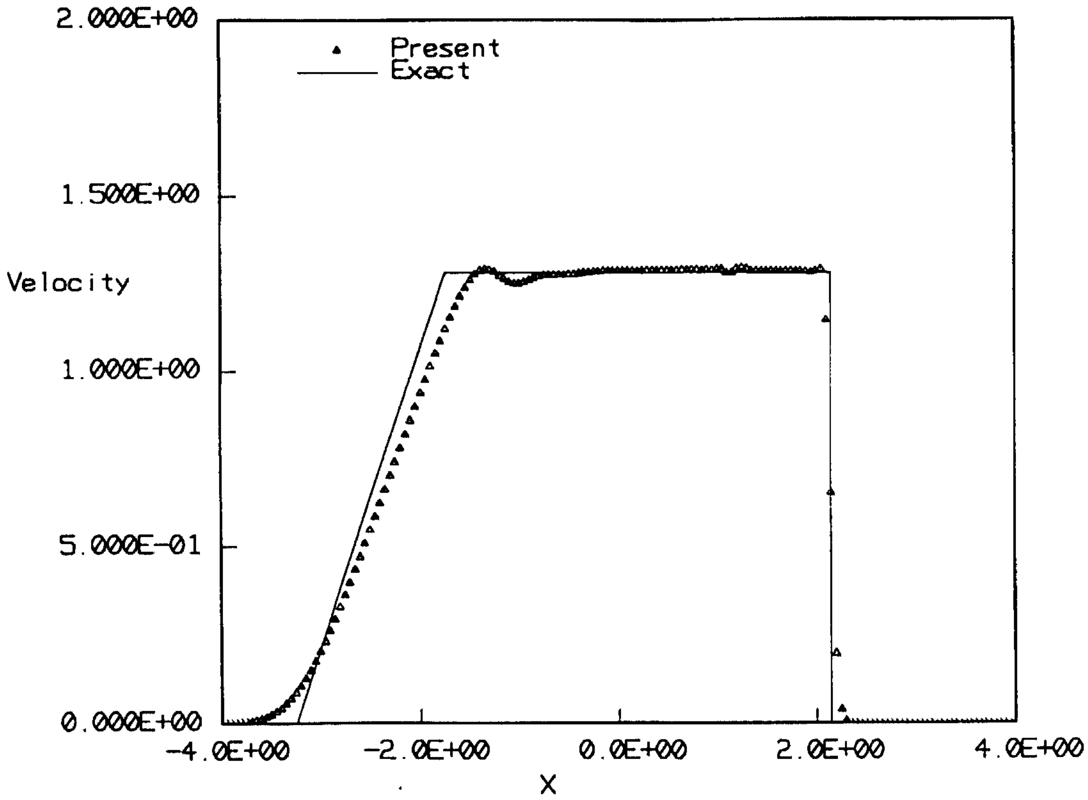

Figure 1 (b). Closed shock tube test case. (t = 0.95)

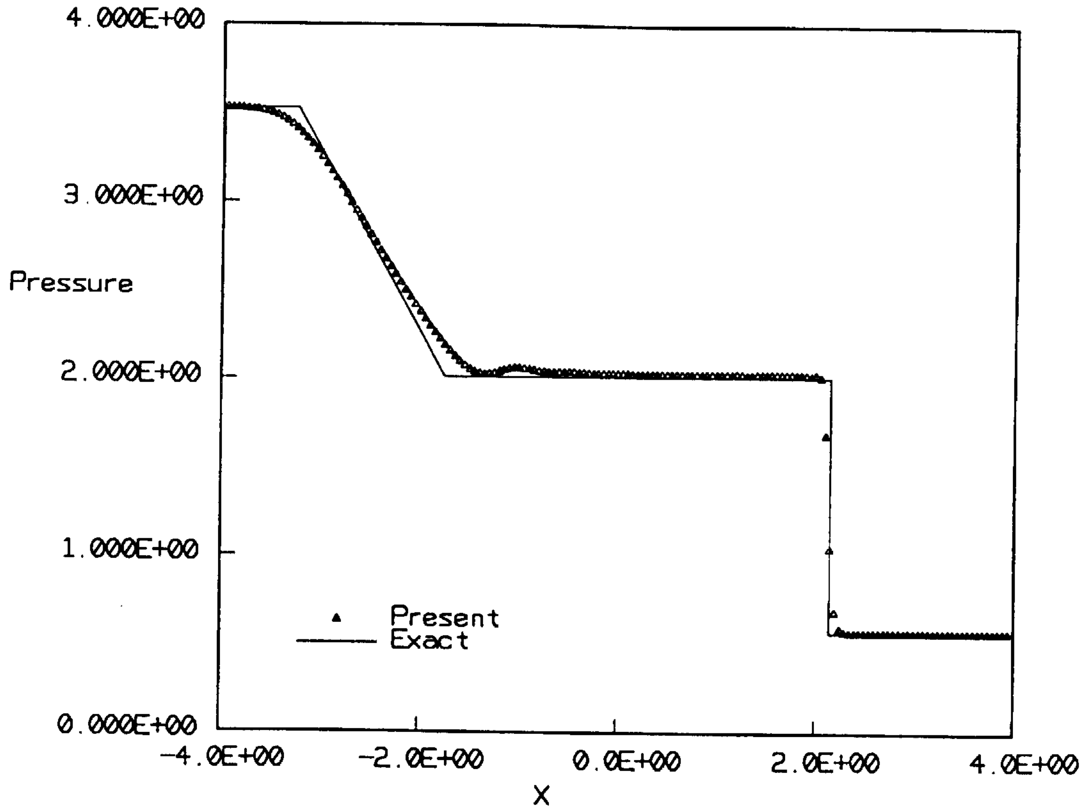

Figure 1 (c). Closed shock tube test case. (t = 0.95)

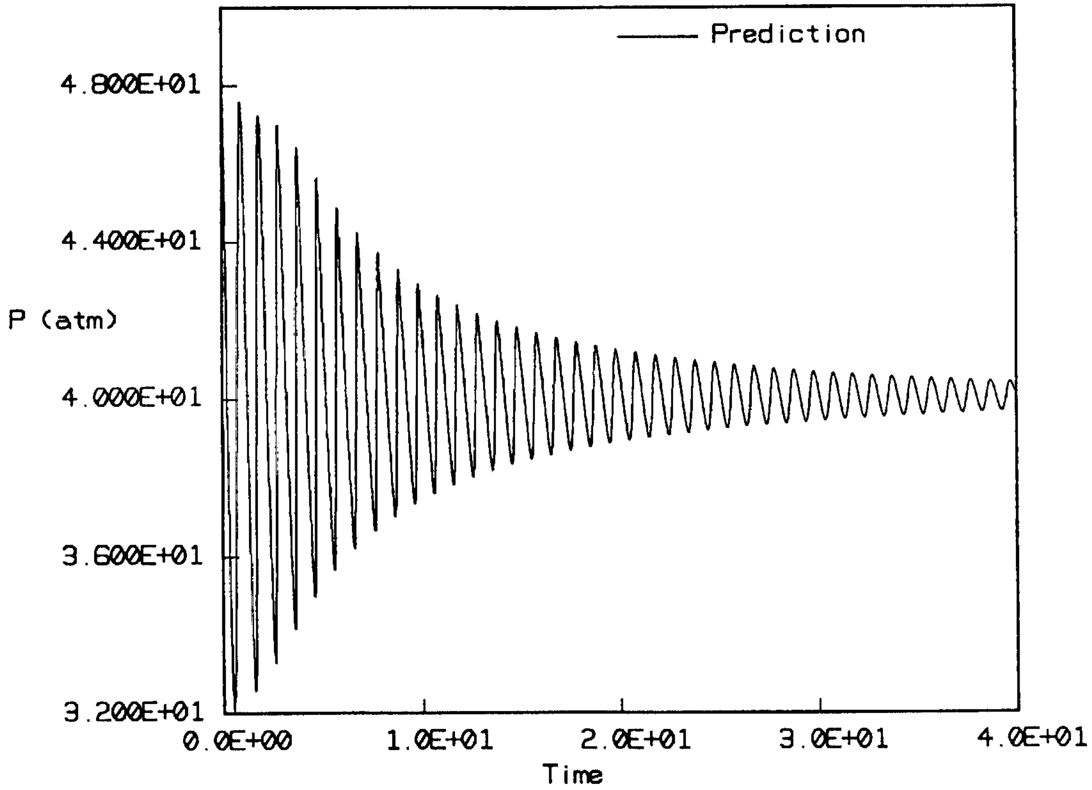

Figure 2. Resonant pipe pressure time-history.

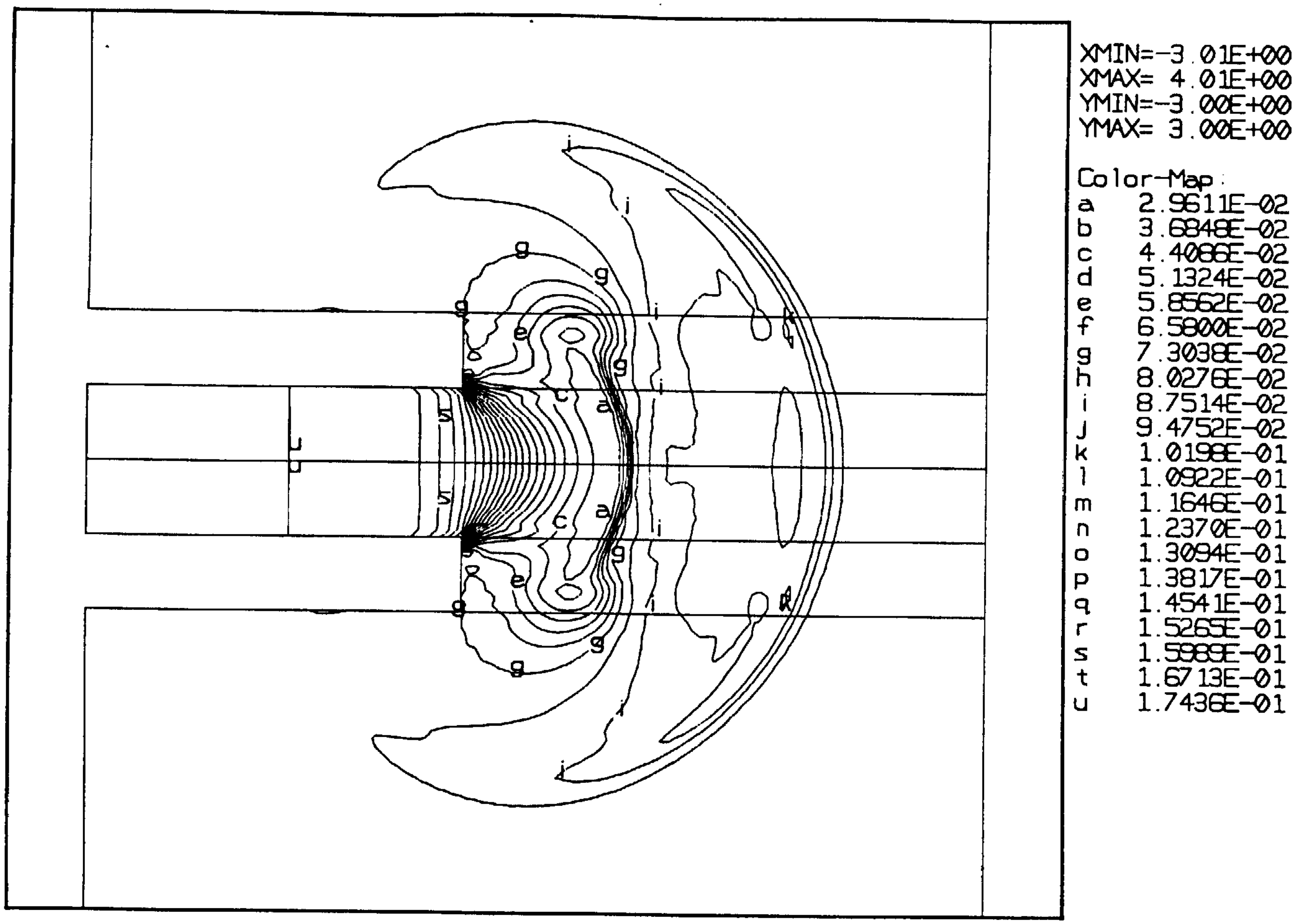

Fig. 3. Blast tube flow field simulation. (a) Density contours.

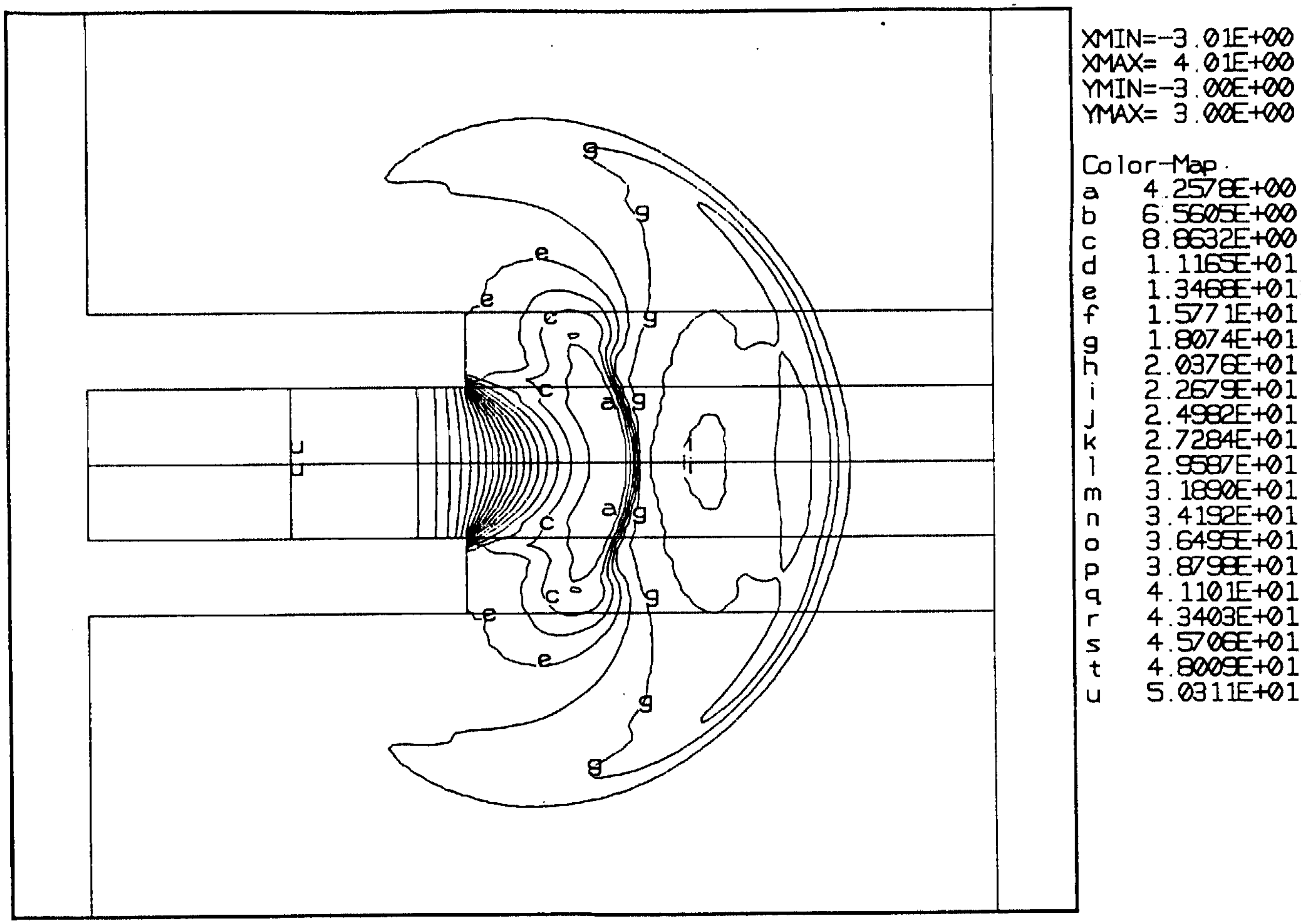

Fig. 3. Blast tube flow field simulation. (b) Pressure contours.
(Time = 0.75 ms)

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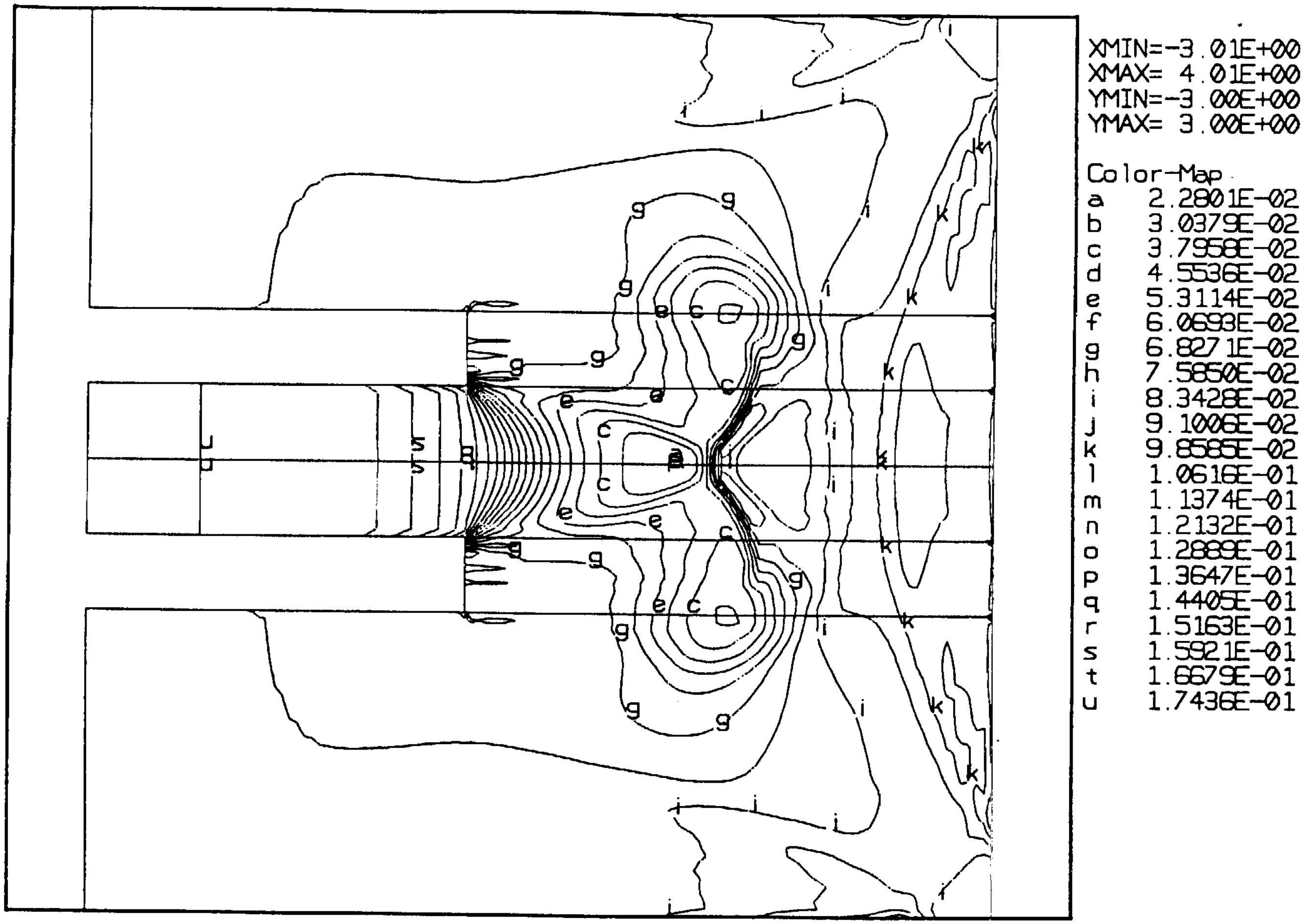

Fig. 4. Blast tube flow field simulation. (a) Density contours.
(Time = 1.50 ms)

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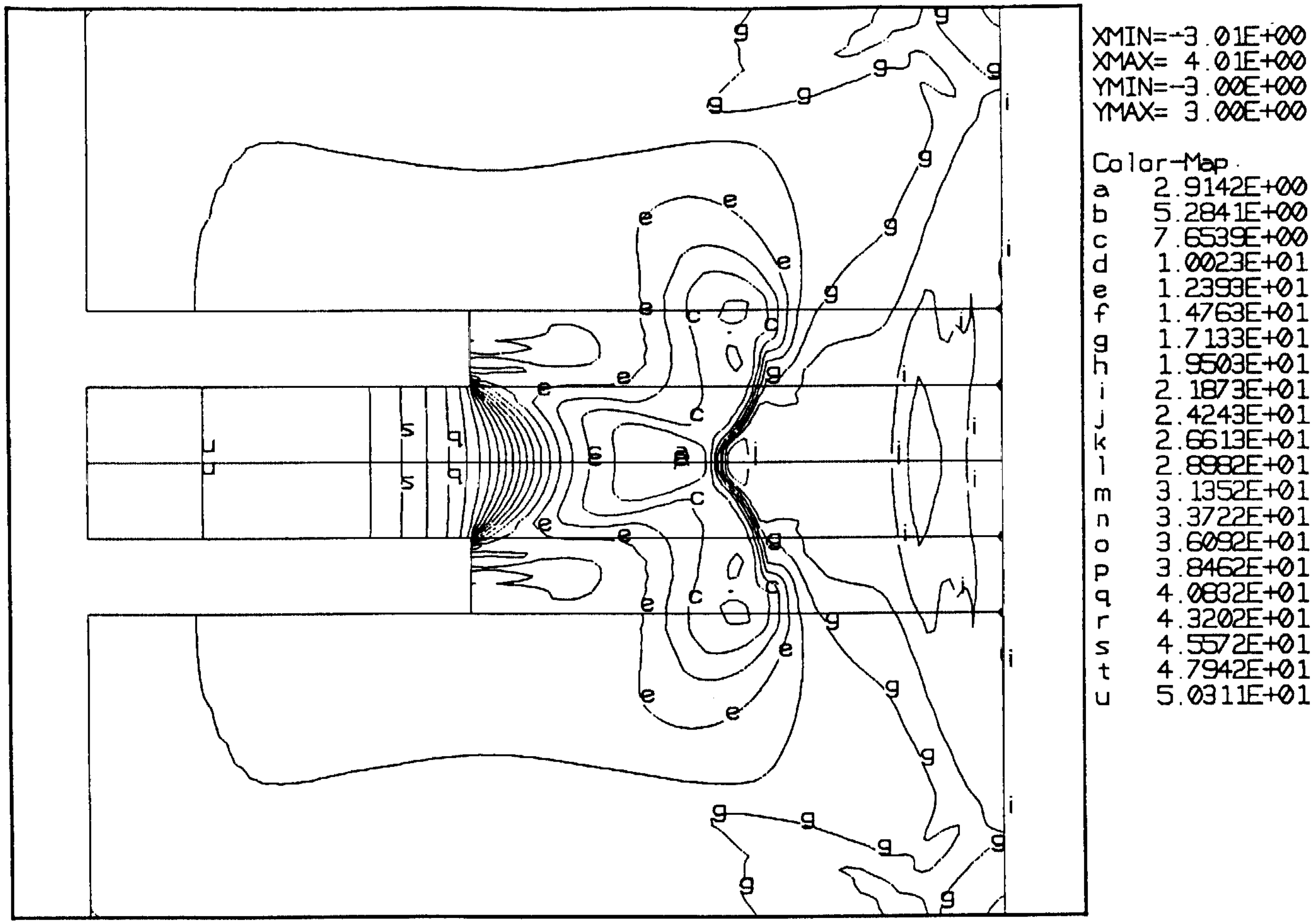

Fig. 4. Blast tube flow field simulation. (b) Pressure contours.
(Time = 1.50 ms)

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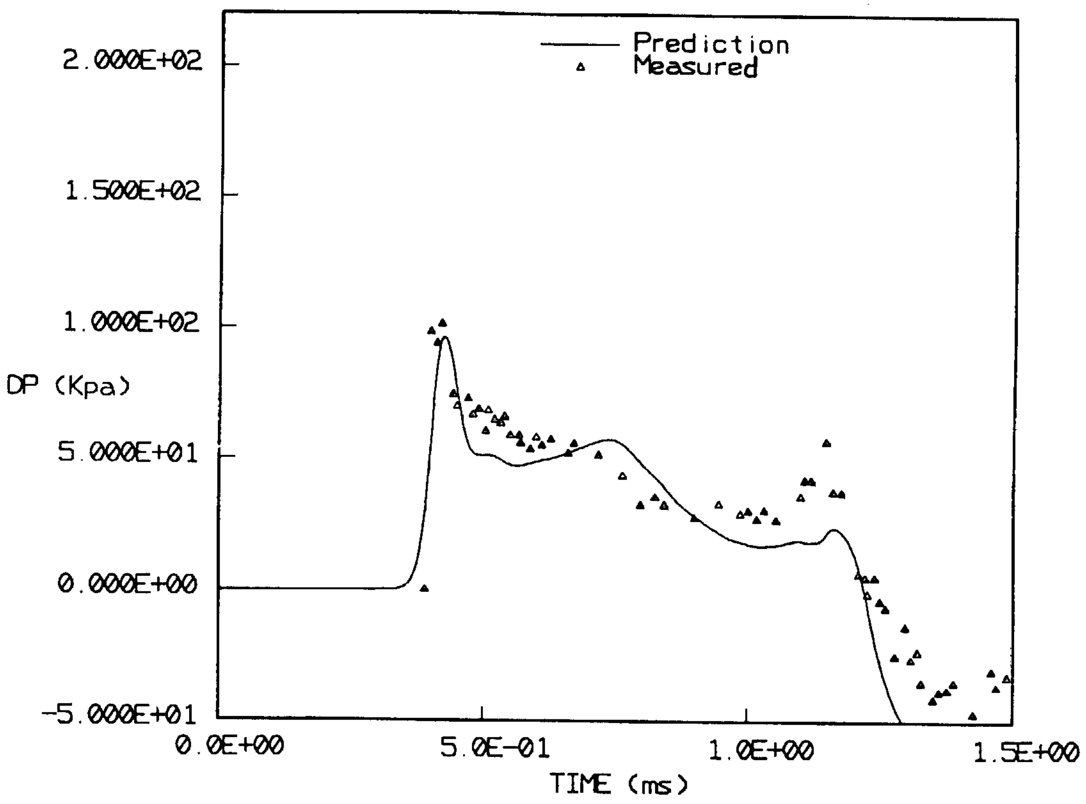

Fig. 5. Comparison of overpressure time history.
(at X/D = 1.51)

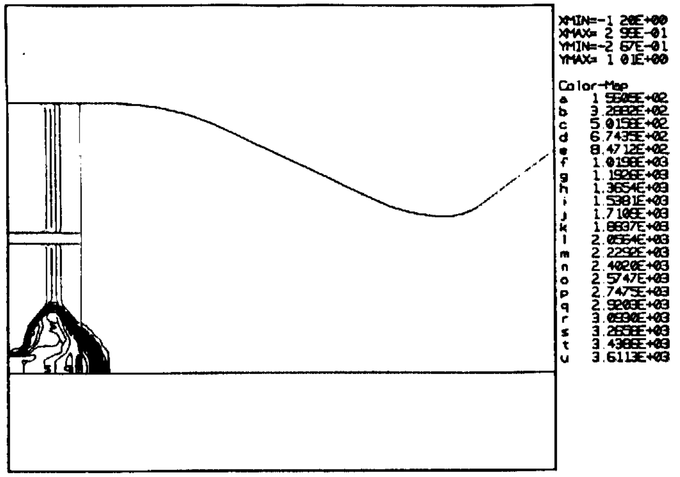

Fig. 6. SSME main combustion chamber test case. (Temp. Contours)
(a) Time = 0.03 ms.

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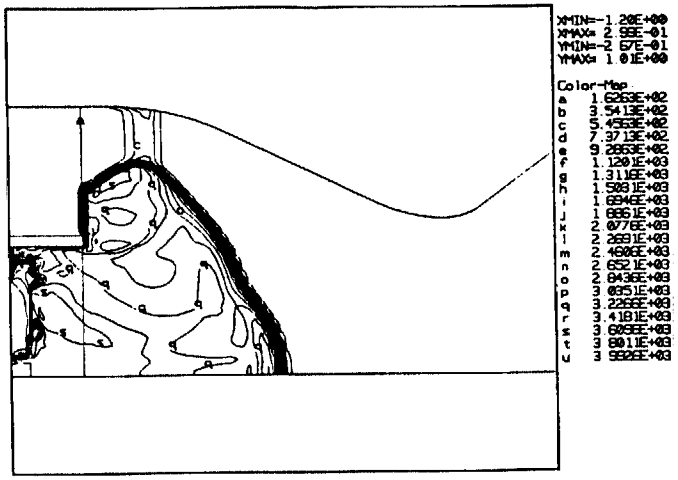

Fig 6 SSME main combustion chamber test case (Temp Contours)
(b) Time = 0.10 ms.

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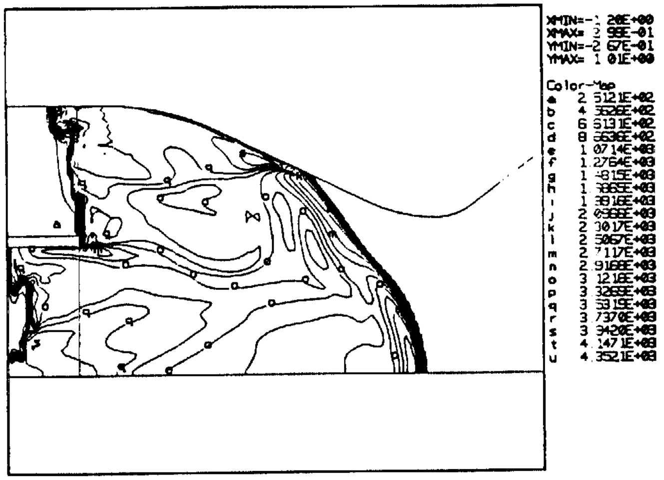

Fig. 6. SSME main combustion chamber test case (Temp. Contours)
(c) Time = 0.15 ms.

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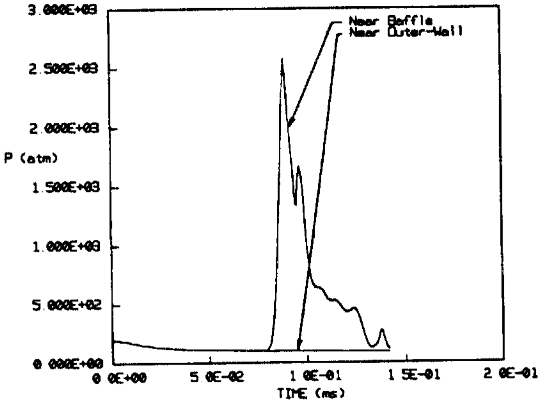

Fig 7 Chamber pressure time-history during start-up.

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SUMMARY AND FUTURE WORK

- TIME-ACCURACY OF THE 3RD-ORDER C-O TVD SCHEME AND PREDICTOR/CORRECTOR SOLUTION ALGORITHM OF THE FDNS CODE HAS BEEN VALIDATED AND DEMONSTRATED IN THE PRESENT STUDY
- LARGE PRESSURE OSCILLATIONS CAN BE EXPECTED DURING H_2/O_2 ROCKET ENGINE START-UP TRANSIENT (THE MAGNITUDE CAN BE REDUCED WITH CORRECT O/F RATIO DISTRIBUTIONS AND START-UP SEQUENCE)
- SPRAY COMBUSTION MODEL WILL BE INCLUDED IN FUTURE STUDY