UNIC UNSTRUCTURED CFD METHODOLOGY DEVELOPMENT

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Abstract

Base heating characteristics is crucial to the success and the overall performance of the X-33 engine. Base heating is important throughout the entire flight trajectory due to the aerospike engine design of X-33. The base region is surrounded by the hot-gas plume, which expands, circulates and impinges on the base. An advanced computation fluid dynamics method is employed in an effort to develop a robust, accurate and efficient tool for the X-33 base heating performance predictions. This computational tool is developed based on a Navier-Stokes flow solver, which is suitable for general complex geometry and includes turbulence, finite-rate chemistry, and radiation models. To fulfill the fast turnaround requirement as a design analysis tool, adaptive mesh refinement method and parallel-computing algorithm are also incorporated in the present model. Case study for the X-33 base-region fluid dynamics and heat transfer characteristics are presented.

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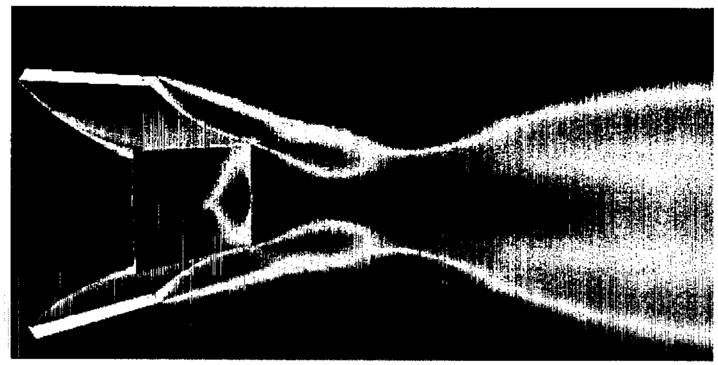

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OUTLINE

- INTRODUCTION
- METHOD OF APPROACH
- NUMERICAL VALIDATION TEST CASES
- DISCUSSIONS AND FUTURE PLAN

Introduction

- Engineering Design Analysis Involves 3-D Complex Flows
- Robust CFD Tools are Critical for Timely Impact in Design Projects
- Structured Multi-block versus Unstructured Mesh CFD codes
- Unstructured Method has the Capability of Automated Mesh Generation
- Parallel Computational Method with Automatic Domain Decomposition
- Has the Potential for Dynamic Load Balancing
- Fully Integrated with Physical Sub-models such as Turbulence, Chemistry, Two-Phase Flow and Radiative Heat Transfer Models, etc.
- Unstructured CFD Method Numerical Accuracy Issues
- Adaptive Mesh and Grid Independent Solution

Method of Approach

- Unstructured Control Volume Navier-Stokes Solver
- Second-Order Spatial and Temporal Discretization Scheme
- Two-Equation Turbulence Models
- Finite-Rate and Equilibrium Chemistry Models
- High-Temperature Gas Thermodynamics Data Base
- Radiative Heat Transfer Models including Ray Tracing Method
- Parallel Computing Method
- Adaptive Mesh Refinement Scheme
- Mixed Element Types Allow Hybrid Mesh Systems
- Metis Domain Decomposition for Parallel Computing

UNIC-UNS Unstructured CFD Code

Governing Equations:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho\, u_j\right)=0$$

$$\frac{\partial \rho\, u_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho\, u_j\, u_i\right)=-\frac{\partial\, p}{\partial\, x_i}+\frac{\partial \tau_{ij}}{\partial x_j}$$

$$\frac{\partial \rho\, h_t}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho\, u_j\, h_t\right)=\frac{\partial}{\partial x_j}\left[\left(\lambda+\frac{\mu_t}{\mathrm{Pr}_t}\right)\frac{\partial T}{\partial x_j}\right]+\frac{\partial\, p}{\partial\, t}+\Phi$$

$$\frac{\partial \rho\, k}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho\, u_j\, k\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial\, k}{\partial\, x_j}\right]+\rho\,(P-\varepsilon)$$

$$\frac{\partial \rho\varepsilon}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho\, u_j\, \varepsilon\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+\rho\,\frac{\varepsilon}{k}(C_1 P-C_2\varepsilon)$$

$$\frac{\partial \rho\, Y_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho\, u_j Y_i\right)=\frac{\partial}{\partial x_j}\left[\left(\rho\, D+\frac{\mu_t}{\sigma_Y}\right)\frac{\partial Y_i}{\partial x_j}\right]+\dot{\omega}_i$$

where

$$\tau_{ij}=\left(\mu+\mu_t\right)\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right)-\frac{2}{3}\rho\, k\, \delta_{ij}$$

$$\mu_t=C_\mu\,\rho\frac{k^2}{\varepsilon}$$

Numerical Schemes

Control Volume Integration:

$$\frac{\partial}{\partial t}\int_{\Omega}\rho\phi\, d\Omega + \oint_{\Gamma}\vec{F}\cdot\vec{n}\, d\Gamma = \oint_{\Omega} S_{\phi} d\Omega$$

Numerical Fluxes (TVD):

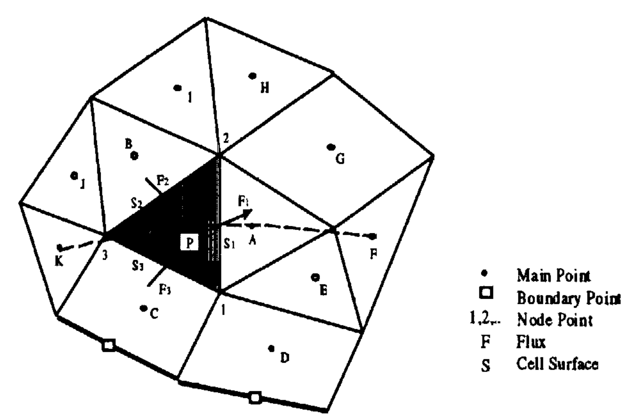
$$\vec{F} = \rho\vec{V}\phi - \mu_{\phi}\nabla\phi$$

$$\oint_{\Gamma}\vec{F}\cdot\vec{n}\, d\Gamma = \sum_{j=k(i)} F_{i,j}\,\Delta\Gamma_j$$

Linearized Equations:

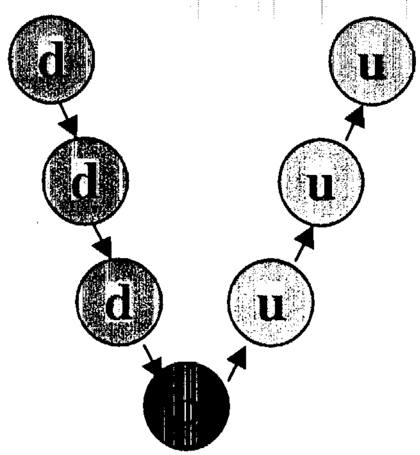
$$\left(\frac{\rho^n}{\Delta t} + A_p\right)\phi_p^{n+1} = \sum_{m=1}^{NB} A_m\phi_m^{n+1} + \frac{(\rho\phi_p)^n}{\Delta t} + S_{\phi}$$

Unstructured Control Volumes

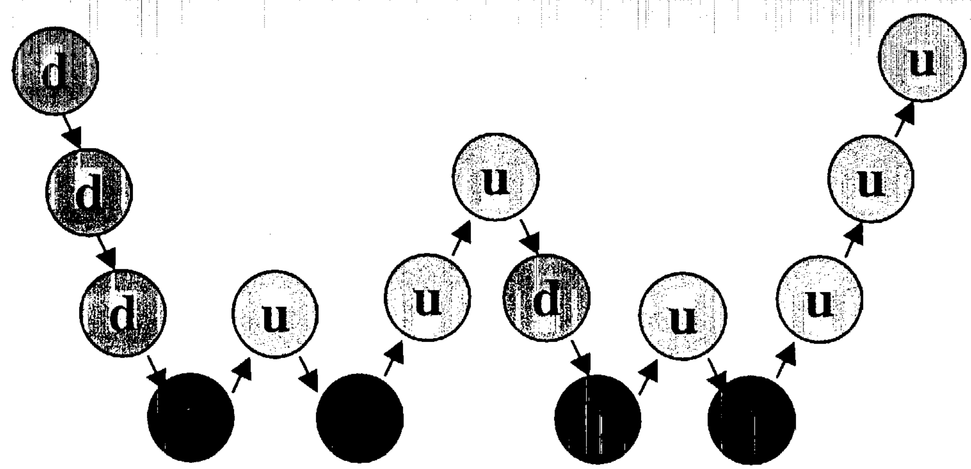


Matrix Solvers

- Bi-CGSTAB -- Efficient for Scalar Transport Equations
- GMRES -- Robust for the Pressure Equation (requires more memory)
- Algebraic Multi-Grid (AMG) Solver -- Efficient, Robust and Scalable in Parallel Computing



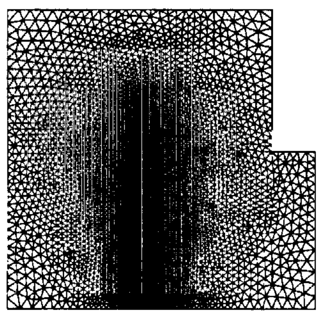
V-Cycle

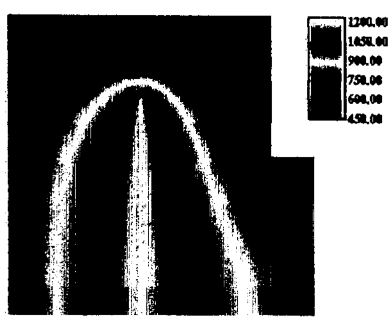


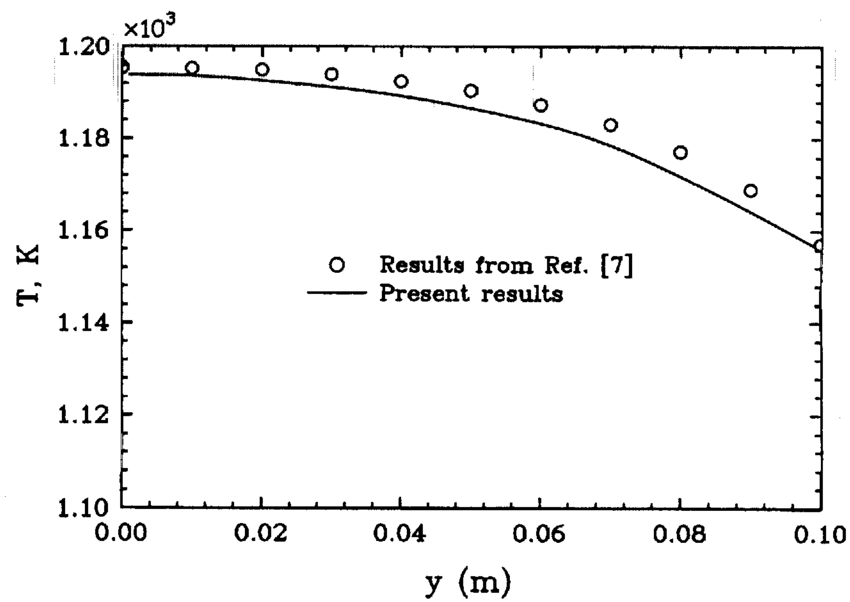
W-Cycle

Radiative Heat Transfer Model

- Discrete Ordinate or Finite Volume Methods
- Computational Efficiency of the Unstructured Radiative Heat Transfer Model has been Improved based on the Structured Version
- Parallel Solution Method is also Implemented and Tested







Adaptive Methods

- **Broadly, there are three categories:**
  - (1) **local enhancement (p-refinement)**
  - (2) **grid movement (r-refinement)**
  - (3) **grid enrichment (h-refinement)**
- **Local enhancement:** This approach captures the details of flow field by enhancing the order of numerical approximation at locations where the solution undergoes abrupt changing. Rarely, it is used in CFD.
- **Grid movement:** It has some limitation, mainly used on transient problems involving moving surface problems. Grid skewness poses the basic problem of this method.
- **Grid enrichment:** Among the adaptive grid methods by enrichment, two techniques are widely employed, grid subdivision and grid re-meshing.

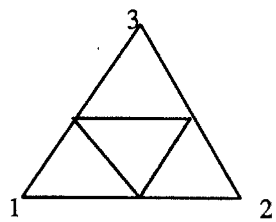
(a) **grid re-meshing:** global and partial.

(b) **grid subdivision:** one of the methods is called as hanging node adaptation, which is used in the present work

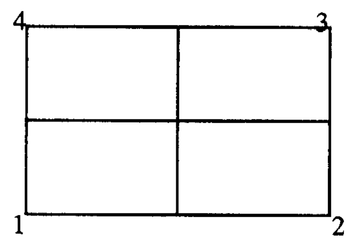
Solution Adaptive Mesh Refinement

- Element Types Included: 2D – Triangles and Rectangles; and 3D – Tetrahedrons, Pyramids, Prisms and Hexahedrons
- Following 2D Adaptive Mesh Refinement Method, 3D Adaptive Mesh Refinement Strategy With Book Keeping Routines has been Implemented and Validated
- Extension of this method to Parallel Mode also shows good Results and Robustness

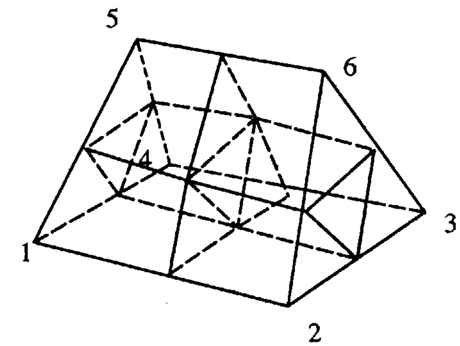
Mesh Refinement Method



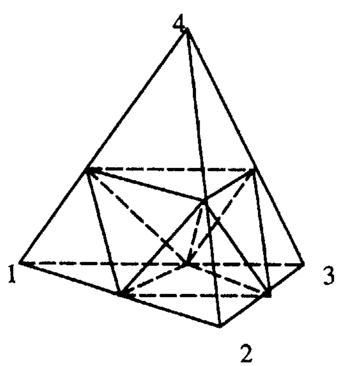
Triangle



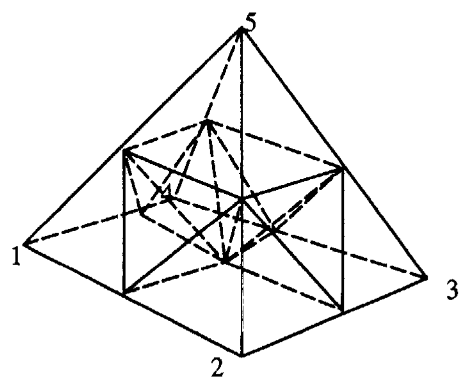
Rectangle



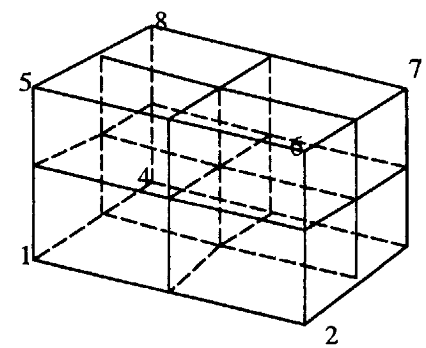
Prism



Tetrahedron



Pyramid



Hexahedron

Refinement and Coarsening

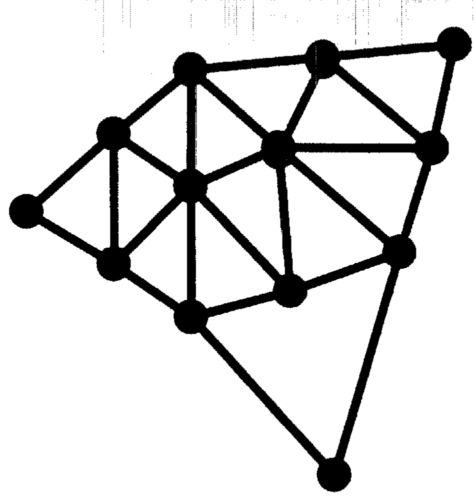
- Mesh refinement or coarsening is determined based on the gradients of a selected field variable.

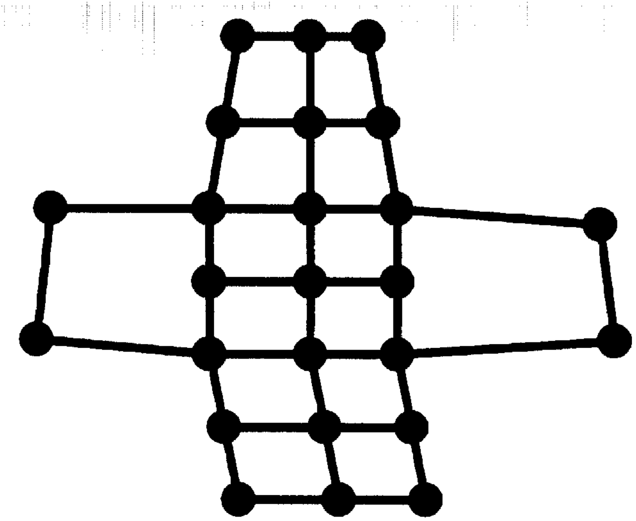
- To ensure accuracy, neighboring cells are not allowed to differ by more than one level of refinement. This prevents the adaptation from producing excessive cell volume changes and makes sure that the positions of the parent and child cell centroids are aligned, thus maintaining the accuracy of the flux evaluations.

- The mesh is coarsening by reintroducing inactive parent cells. This process is equivalent to coalescing the child cells of the previously subdivided parent cell. An inactive parent cell is restored if all its children are marked for coarsening. The cell field variables can be obtained by using the volume weighted average of children's cell variables.

Smoothing Strategy

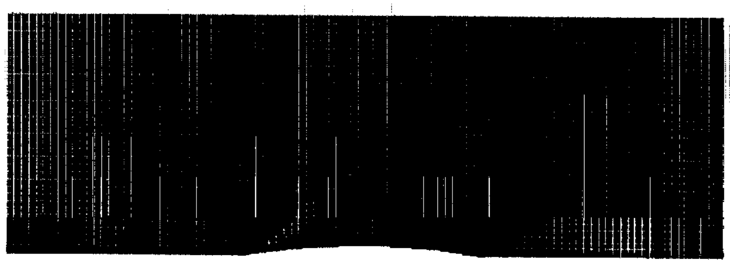
- To assure a smooth variation of cell volume, additional cells are refined based on the number and/or relative position of neighboring cells that have been subdivided. When a cell is coarsened, the same rule is followed to ensure that no excessive cell volume variations occur.

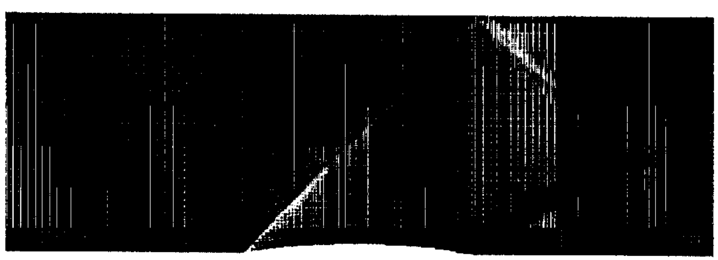


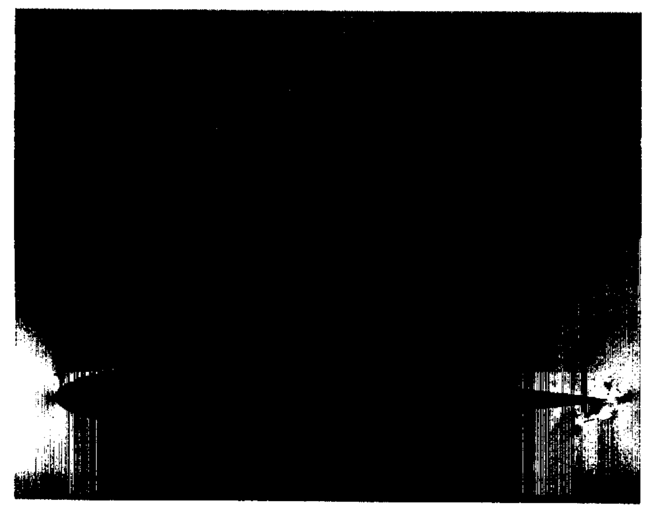


Adaptive Mesh Refinement

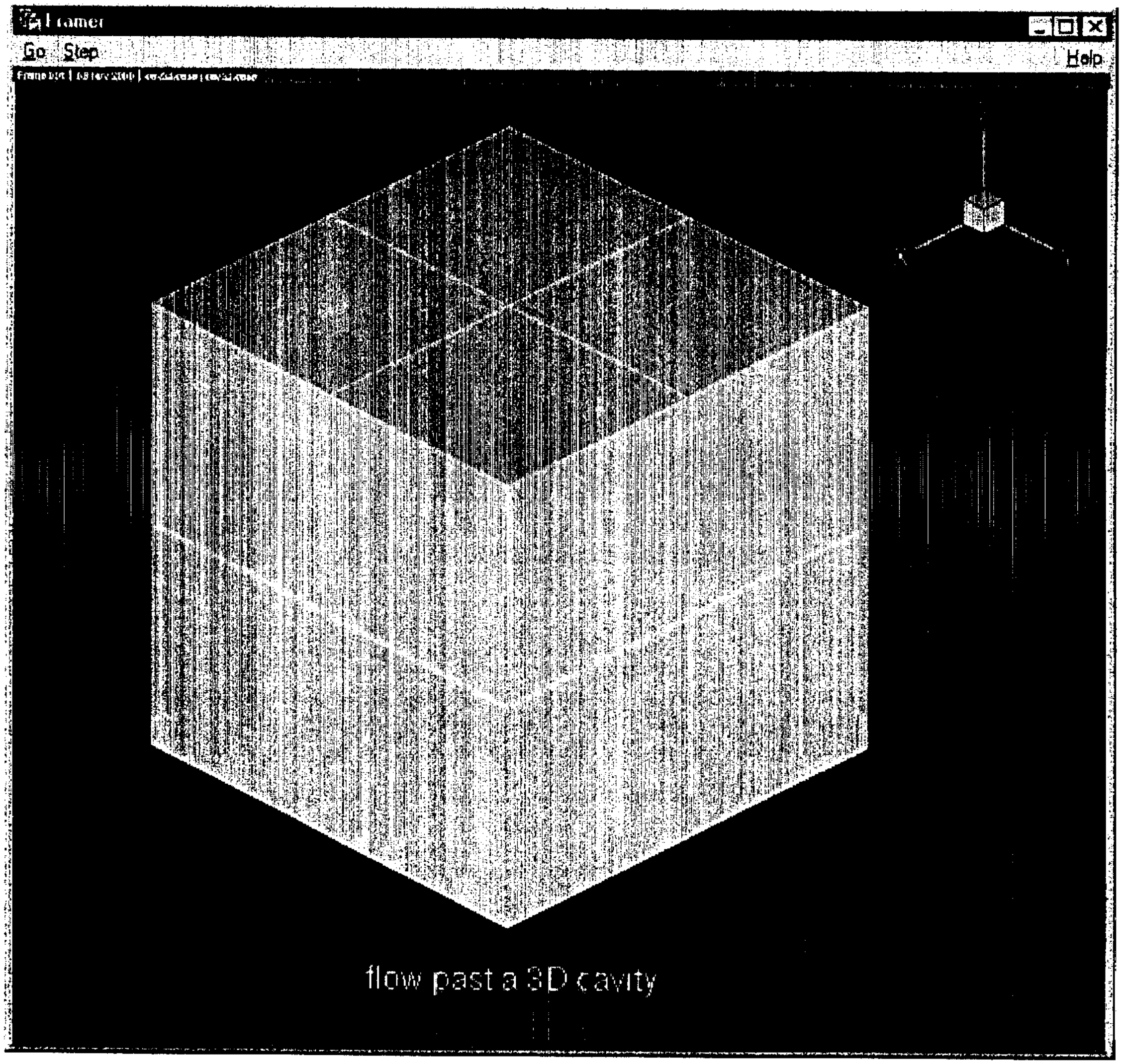
- 2D and 3D Schemes Completed
- Adaptive in Parallel Computing Implemented
- Formulating Mesh Adaptive Variables



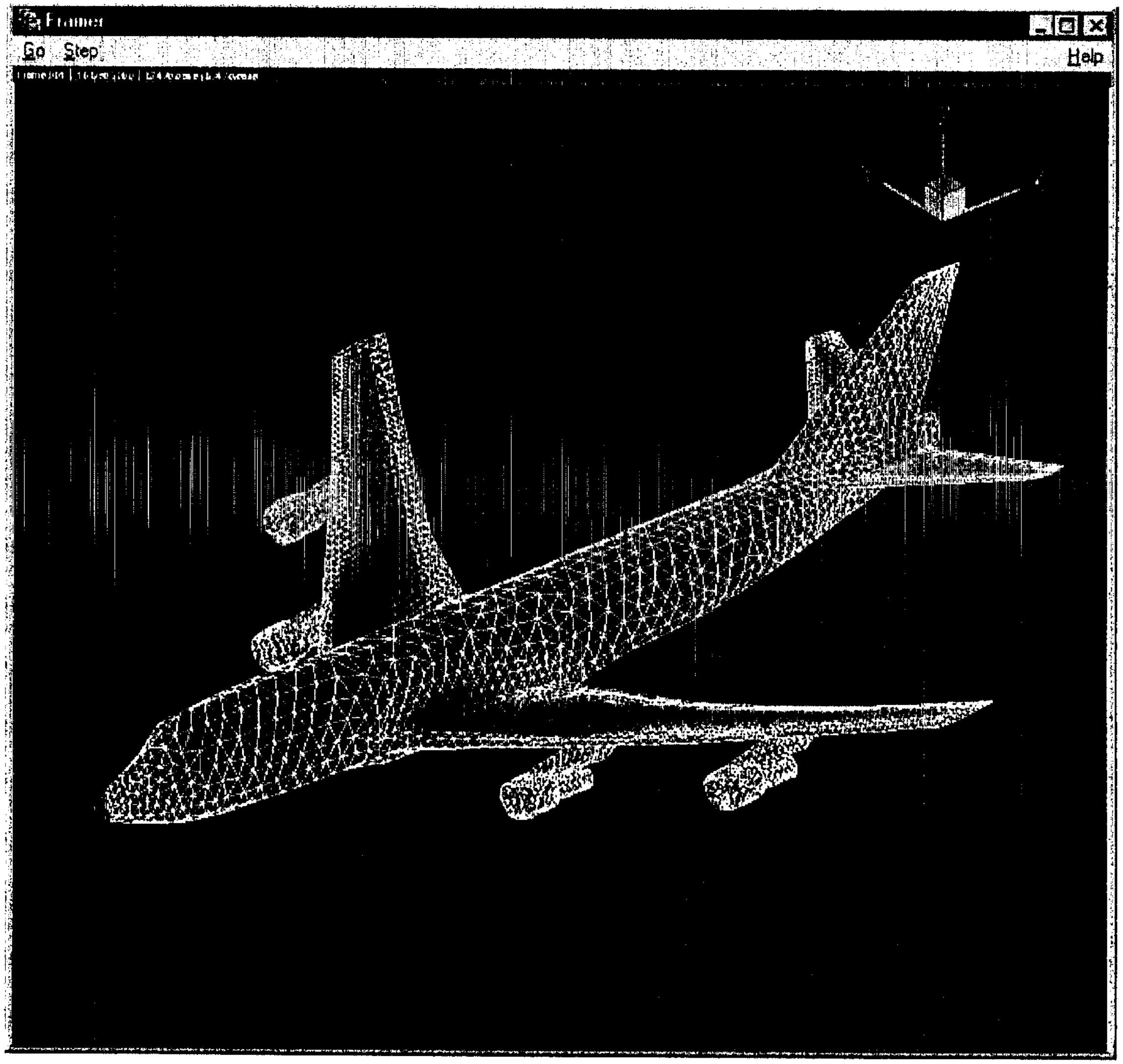




3-D Adaptive Refinement Example

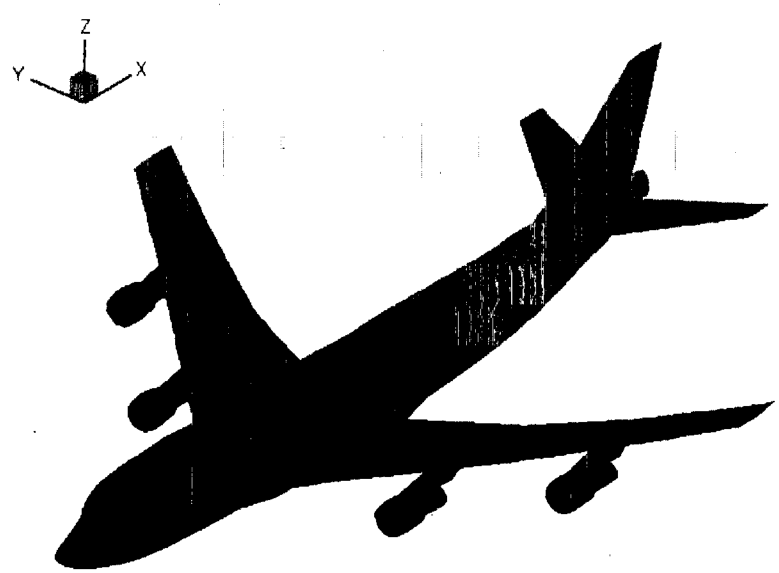


3-D Adaptive Refinement Example

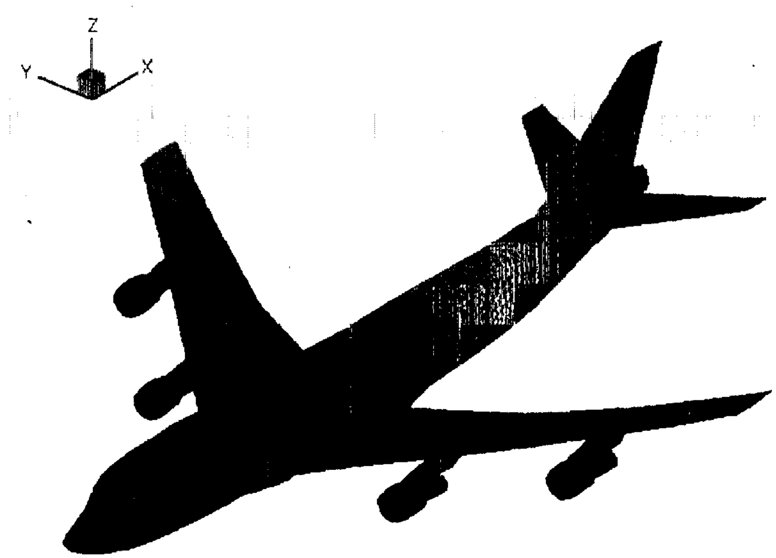


Testing of Parallel with Mesh Adaptation Strategies

- Satisfy Mesh Refinement Criteria (Level Jump Conditions)
- Parallel Mesh Level Information Cross Domain Interfaces



Parallel W/O Adaptation

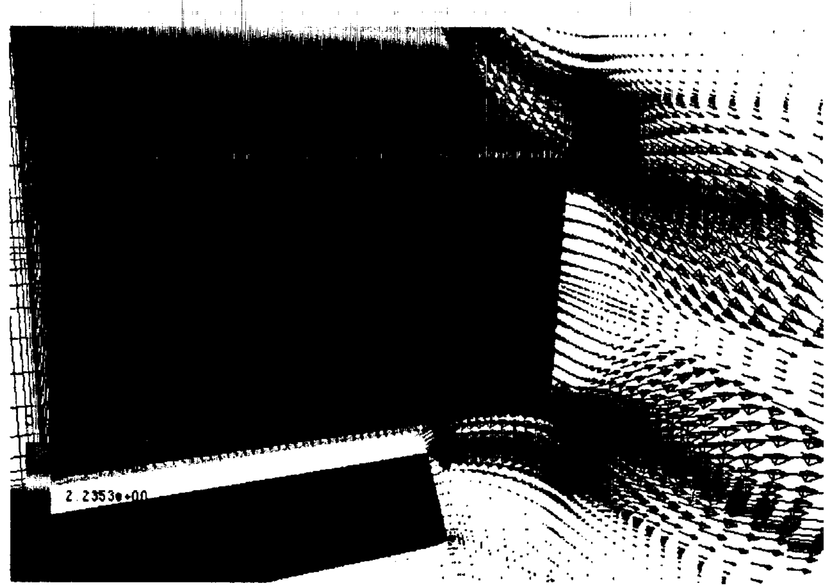


Parallel With Adaptation

X-33 Sub-scale Model Base-Heating Test Cases

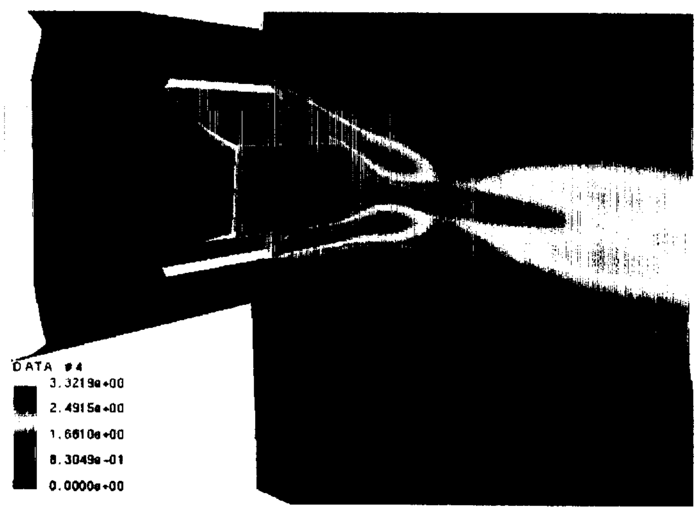
- Sub-scale Model: 2.25% of X-33 Base Region
- Cabin Pressures Currently Considered (psi)

  14.515, 9.329, 6.827, 2.924, 1.365
- Engine Chamber Pressure / Temperature = 838.24 psi / 3450 K
- Chemistry Model: 7-Species, 9-Reaction Finite Rate Chemistry

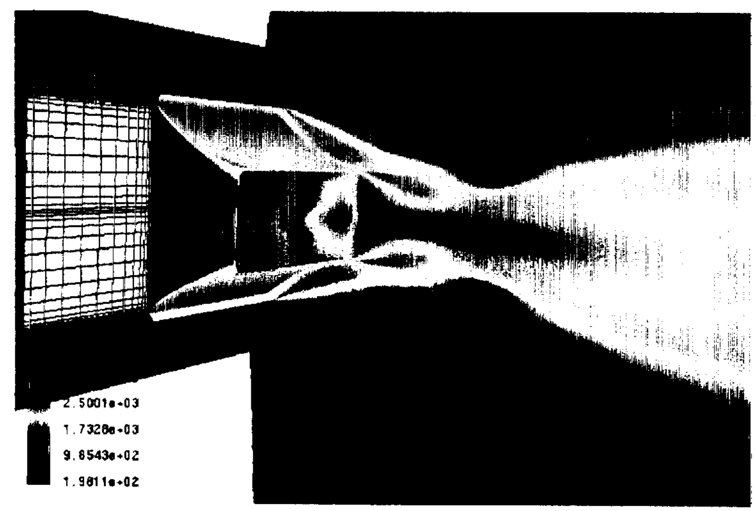


Base Flow Solutions

- Total Number of Grid Points = 0.5M
- 8500 Time Steps for Convergence (Monitoring Base Heat Flux Values)
- Solutions for 14.515 psi Cabin Pressure Shown



Mach Number

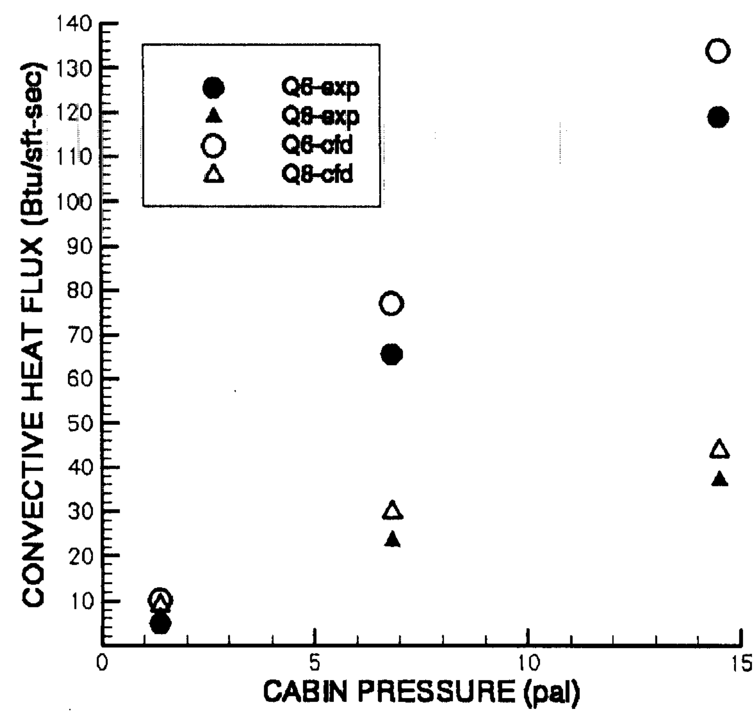


Temperature (K)

Base-Heating Data Comparisons

- The Predicted Heat Flux Values are slightly higher than Data
- CFD Solution Reflects The General Trend of Heat Fluxes with Cabin Pressure

Preliminary Results:



Discussions and Future Plan

- The Current Domain Decomposition Strategy works fine for General Aerodynamics Applications (Equally Balanced Loads based on Element Number and Connectivity)
- Smart Load Balancing Strategy is needed for Problems Involve Chemical Reactions, Spray Combustion, Radiation, etc.
- Dynamic Load Balancing Method will be Investigated
- Validate Parallel Schemes for the Particulate Two-Phase Flow Model
- Continue Benchmark Validation Study to include Applications in Propulsion Systems