2013 DOE
Merit Review

2013 KIVA Development

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Los Alamos National Laboratory
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Project ID # ACE014

LA-UR-13-21976

Overview

Timeline

- 10/01/09
- 09/01/14
- 65% complete

Budget

- Total project funding to date:
  - 2000K
  - 640K in FY 12
  - Contractor (Universities) share ~40%
- Funding to date for FY13 - 210K
- Funding anticipated FY13 – 763K

Barriers

- Improve understanding of the fundamentals of fuel injection, fuel-air mixing, thermodynamic combustion losses, and in-cylinder combustion/ emission formation processes over a range of combustion temperature for regimes of interest by adequate capability to accurately simulate these processes
- Engine efficiency improvement and engine-out emissions reduction
- Minimization of engine technology development
  - User friendly (industry friendly) software, robust, accurate, more predictive, & quick meshing

Partners

- University of New Mexico- Dr. Juan Heinrich
- University of Purdue, Calumet - Dr. Xiuling Wang
- University of Nevada, Las Vegas - Dr. Darrell W. Pepper

FY 09 to FY 14 KIVA-Development

Objectives

- **Robust, Accurate Algorithms in a Modular Object-Oriented code**–
  - Relevance to accurately predicting engine processes to enable better understanding of, flow, thermodynamics, sprays, in easy to use software for moderate computer platforms
    - **More accurate modeling requires new algorithms and their correct implementation.**
      - Developing more robust and accurate algorithms
        - To understand better combustion processes in internal engines
      - Providing a better mainstay tool
        - improving engine efficiencies and
        - help in reducing undesirable combustion products.
      - Newer and mathematically rigorous algorithms will allow KIVA to meet the future and current needs for combustion modeling and engine design.
      - Developing Fractional Step (PCS) Petrov-Galerkin (P-G) and Predictor-Corrector Split (PCS) *hp*-adaptive finite element method
      - Conjugate Heat Transfer providing
        - More accurate prediction in wall-film and its effects on combustion and emissions under PCCI conditions with strong wall impingement.
        - Providing accurate boundary conditions.
- **Easier and quicker grid generation**
  - **Relevant to minimizing of engine technology development**
    - CAD to CFD via Cubit Grid Generation Software – still in development – some issues
    - KIVA-4 engine grid generation (pretty much automatic but some snapper work around difficult).
    - Easy CAD to CFD using Cubit grid generator - *hp*-FEM CFD solver with overset actuated parts and new local ALE in CFD, removes problems with gridding around valves and stems.

Milestones for FY 10- FY13

06/09 – Started Researching Fractional Step CBS method (switched to Pressure Stabilized PCS with P-G)
09/09 – 2D and 3D P-G Fractional Step (PCS/CBS) Finite Element Algorithm Developed.
01/10 – *h*-adaptive grid technique/algorithm implement in PCS-FEM method for 2D
02/10 – *h*-adaptive grid technique/algorithm implement in PCS-FEM method for 3D
02/10 – *hp*-adaptive FEM Algorithm & Framework: continued development and changes.
02/10 thru 09/10 – Successful at meeting standard incompressible benchmark problems.
05/10 – Multi-Species Transport testing in PCS-FEM algorithm.
10/10 – P-G found to be more flexible than CBS stabilization via benchmark comparisons.
12/10 to 03/12 – Inserting PCS algorithm/coding into *hp*-adaptive Framework.
01/11 – FY11 Engineering documentation and precise algorithm details published (available publicly from library reference).
05/11 – Compressible flow solver completed, benchmarked inviscid supersonic
09/11 – Completed incorporating Cubit Grids for KIVA-4 and the FEM method too Cubit2KIVA4 & Cubit2FEM
10/11 – 2-D subsonic and supersonic viscous Flow benchmarks with turbulence
10/11 – Local ALE for immersed moving parts with overset grid system 2-D
12/11 – Benchmarked 2-D Local ALE for velocity
12/11 – Parallel Conjugate Heat Transfer KIVA-4mpi
01/12 – 2-D *hp*-adaptive PCS FEM validated subsonic flow
02/12 – Injection Spray model into the PCS FEM formulation

08/12 – 2&3-D hp-adaptive PCS FEM completed – validated subsonic & transonic flow

09/12 – Droplet Evaporation

10/12 – 2-D supersonic turbulent flow validation

10/12 – Analytic (similarity solution process) Pressure for 2-D ALE validation

11/12 – Droplet Break-up, Collision, Wall-film, Spread and Splash, partially rewritten and put in for FEM method

01/13 – Chemistry model fully implemented with FEM reformatting and some testing in PCS FEM formulation

01/13 – OpenMP parallel system in PCS FEM formulation with testing

01/13 – 3-D Local ALE method for immersed moving parts

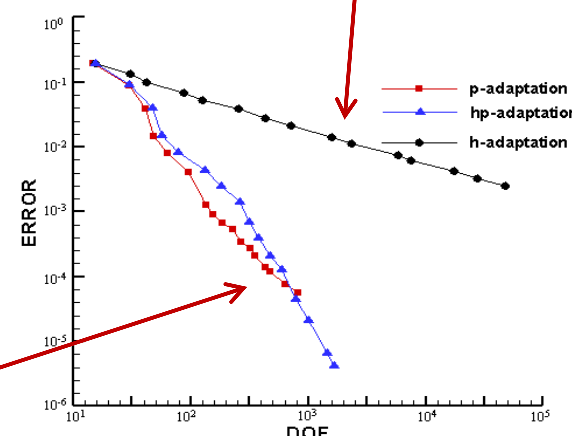
03/12 to 12/12 – Presentations ASME V&V And Papers accepted to ICHT and CTS

Approach

- **What if we had a turbulent reactive flow modeling software for engines that could provide:**

1) **Faster grid generation - CAD to CFD** grid in nearly a single step
2) 1 pressure solve per time step - always
3) Exactly models curved surfaces
4) **Mesh never tangles – Robust and 2nd order accurate** moving parts
5) Higher order accurate - **2nd and better spatial accuracy - everywhere & always**
6) **3rd order accuracy** for advection terms
7) **Minimal communication** for faster processing
8) **Evolving solution error drives grid**:
   i. **Resolution and higher-order approximation**
9) Accurate ***KIVA multi-component Spray model***
10) Eulerian, with **better/good turbulence modeling**
11) *hp*-adaptive FEM – **exponentially grid convergent**

Error as function(*grid size*)
KIVA-3v, or 4 type method



hp-adaptive **FEM**
– exponential grid convergent !

A lot to ask!
How can we get so many numerical win-win-win combinations?
The new discretization allows this.

Development Approach and Accomplishments

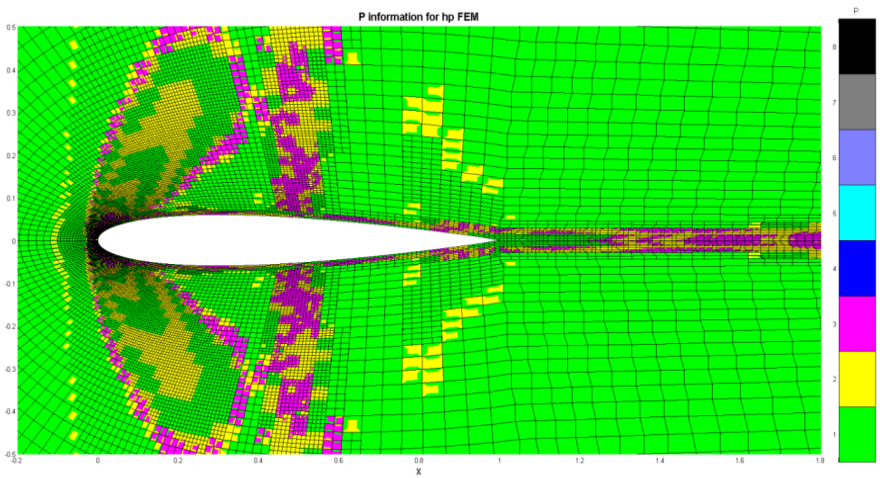
- Approach for Robust and Accurate Numerical Simulation:
  - Algorithms and their implementation (discretization) must be of sufficient accuracy and robustness to do be able to perform turbulence and spray modeling in a complex domain.
    - Yes, we need better models for spray and turbulence, on a robust and accurate platform.
  - More accurate modeling requires either 1) altering existing KIVA or 2) new algorithms. We have proceeded on both paths but, with greatest emphasis and promise by using newest algorithms and leveraging recent research.
- Development Process
  - Understanding of the physical processes to be modeled
    - Mathematical representations and evaluation of appropriate models.
    - Guiding engineering documents
      - Assumptions inherent in particular model and methods
      - Ability of *hp*-adaptive PCS method, the mathematical formulation, and its discretization to model the physical system to within a desired accuracy.
      - The ability of the models to meet and or adjust to users' requirements – chose
      - The ability of the discretization to meet and or adjust to the changing needs of the users.
      - Effective modeling employs good software engineering practices.
        - Modularity, Documentation, Levelized (under-the-hood)
  - Validation and Verification (V&V) – meeting requirements and data.
    - Verification via known algorithm substitution
    - Validation and development process
      - Benchmark Problems that exercise all code in all flow regimes
      - Analytic Solutions when available
      - Piece by piece validation, removing as much coupled physics as is possible
        - Isolate algorithms – unit tests as much is as possible.
      - Validating the whole in addition to separate piece-wise validation

FY-13 Technical Accomplishments

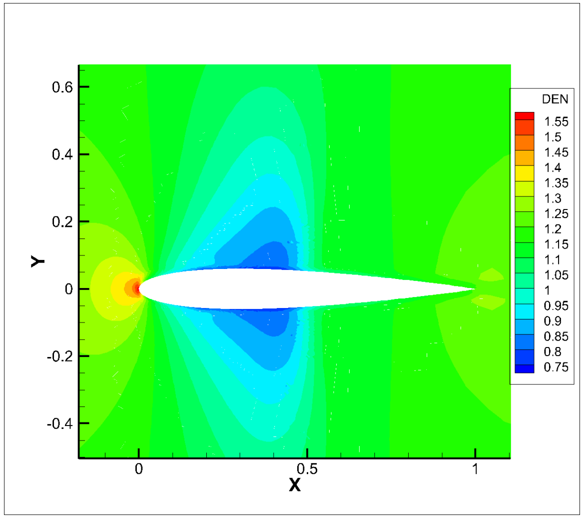
- Accurate and Robust Turbulence Reactive Flow Combustion Modeling
  - 2-D and 3-D PCS *h*-adaptive and *hp*-adpative FEM codes are coded:
    - Modeling –Benefit of Eulerian system with 2nd order-in-time algorithm
    - Performed without large system of linear equations to solve!
    - Essentially no Numerical dispersion – FEM allows for precise measure and removal prior to solution advancement.
    - 1 pressure solve per time step : Semi-implicit or an Explicit modality good for multi-core threading.
    - Equal-order isoparametric elements: exactly models curved surfaces.
    - k-ω turbulence model FY-09 & FY-10 (Carrington, et al 2010) *in hp-FEM formulation (FY12)*
    - *k-ε* blended low Reynolds (Wang, Carrington, Pepper 2009) .
    - New wall function system for both 2D and 3D - compressible (variable density in FY11).
    - PCG Solver & in-situ stationary preconditioning (FY 10)
    - Verification complete - Known algorithm substitution and benchmark problems solution
    - *Validation and continued development and error/bug removal - Benchmarks Problems*
  - *OpenMP protocol implemented* and tested (multi-core CPU processors) – 3x speed-up.
  - *More accurate KIVA multi-component Spray -* FEM Lagrangian Particle Transport
    - *Grid scale accurate within each element, continuous properties*
    - *Validation started.*
  - KIVA Chemistry implemented - testing started.
  - New accurate & robust 3-D Local Arbitrary Lagrangian Eulerian (ALE) for moving parts on an Eulerian FEM fluids discretization - Validated!
  - *Cubit (Sandia National Lab) and MeshTool (ANSYS) grid generation (automatic)* for *the PCS FEM* method

PCS FEM V&V - Subsonic flow regime

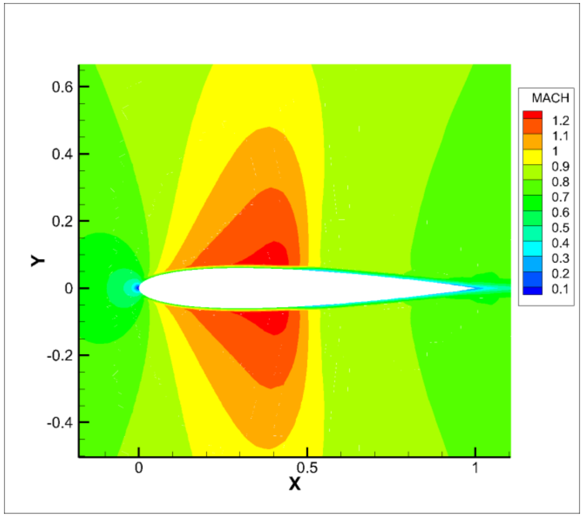
- NACA 0012 airfoil test
  - Mach = 0.8 & α = 0
  - Time dependent solution
  - P-G stabilization.
  - Multi-species testing, 2 species at inlet.



hp-adapted domain



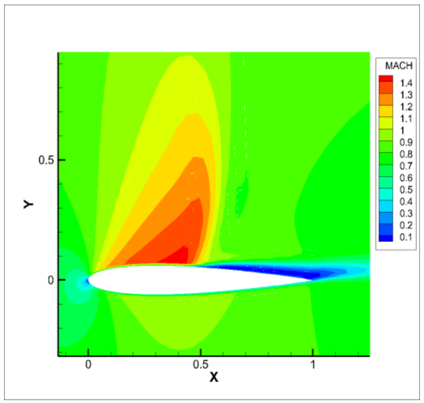
Density



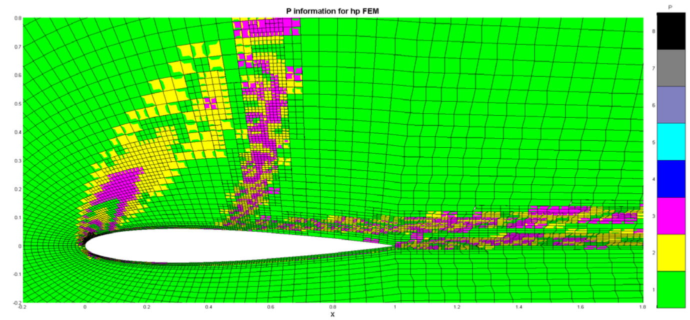
Local Mach Number

*hp-a*daptive PCS FEM for 2-D NACA Airfoil at Subsonic

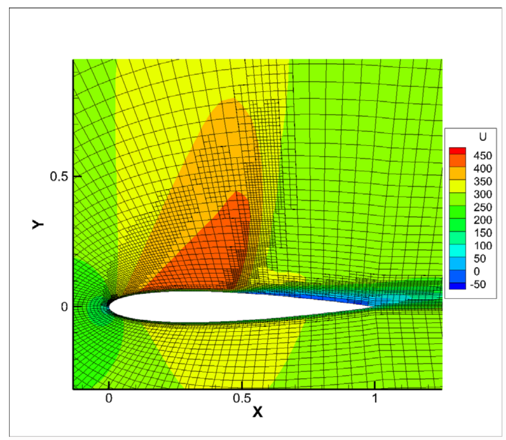
- Mach = 0.8 & attack angle α = 4º
  - Time dependent solution
  - Gambit generated initial grid
  - Agreement with data



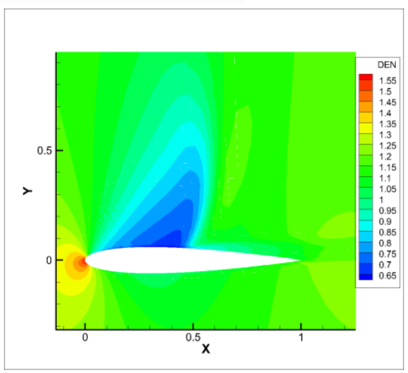
Local Mach



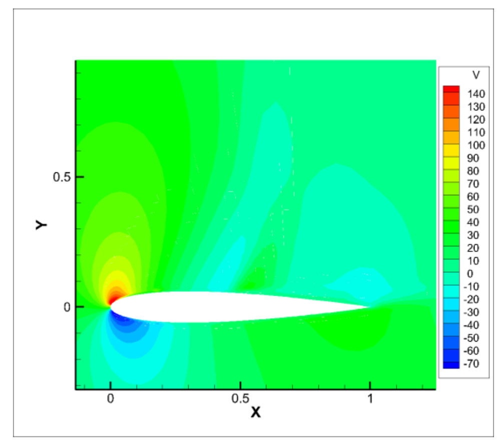
Final mesh *hp*-adaptive
(polynomial order shown in color)



Velocity components



Density



- Also continues to demonstrating Solver Capability
  - Truly curved and complex domains

*hp-a*daptive PCS FEM for 3-D NACA Airfoil at Subsonic

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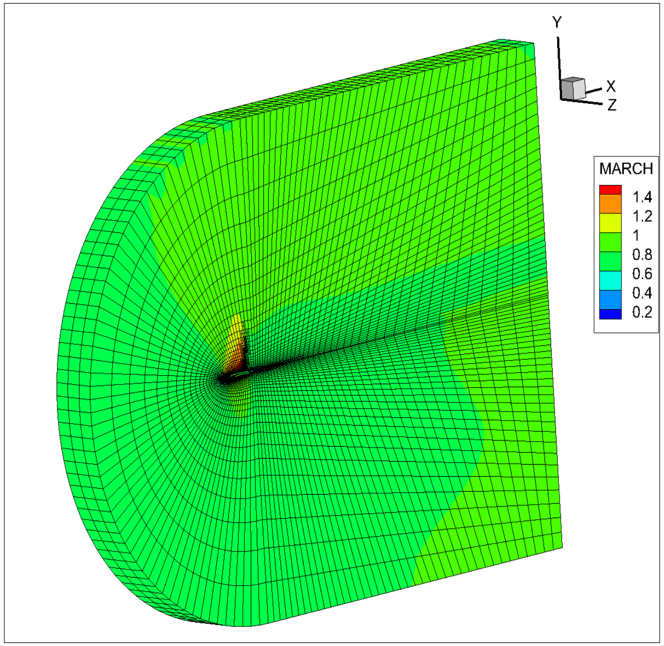
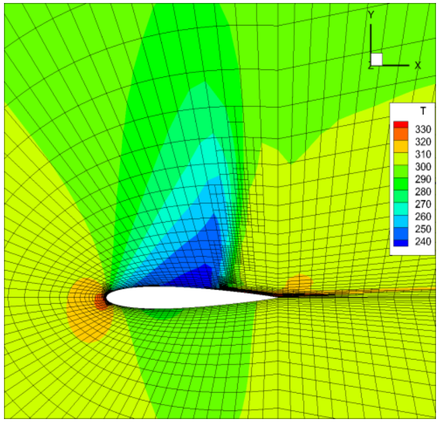
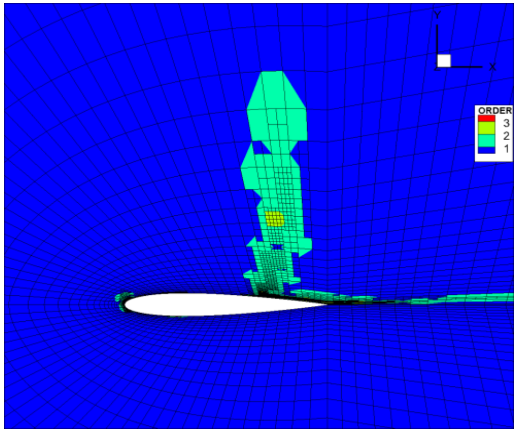
- Mach = 0.8 & attack angle α = 4°
  - Time dependent solution
  - Gambit generated initial grid
  - Agreement with data



Local Mach

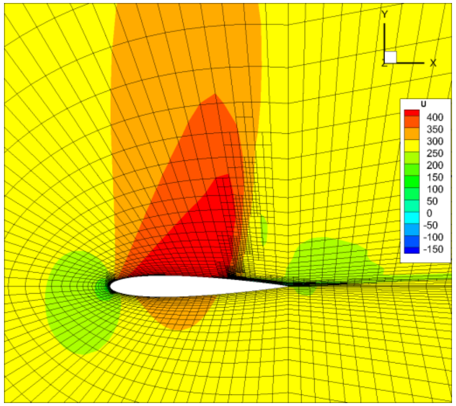


Temperature



Final mesh *hp*-adaptive
(polynomial order shown in color)

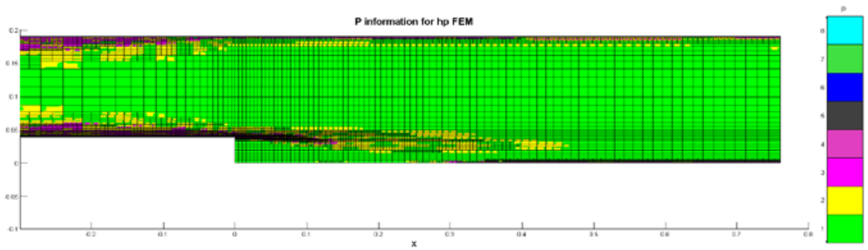
Velocity components



- Also continues to demonstrating Solver Capability
  - Truly curved and complex domains

Parallel *hp-a*daptive PCS FEM – OpenMP

The tested case is backward facing step simulation with Re=28,000, which is 15979 elements, 15975 vertex nodes, 60976 high order nodes, 90477 total DOF.

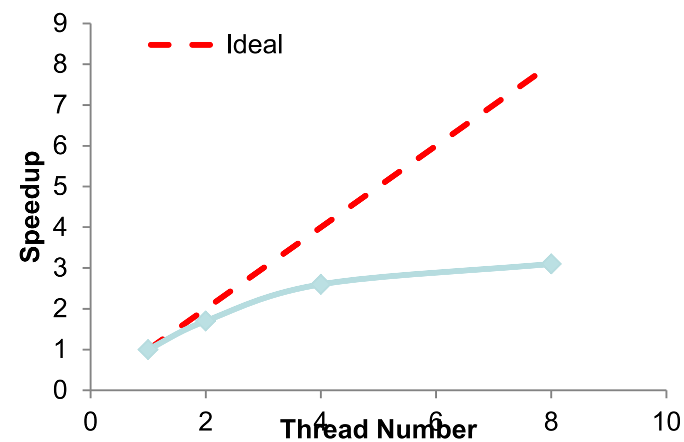


Functions	Time (Seconds)	Percentage (%)
Residual	1.58×10^4	24.4
Solver	1.60×10^4	24.7
Assemble	1.04×10^4	16.1
K-Omega turbulent assemble	1.05×10^4	16.2
Velocity correction	7.07×10^3	10.9
Turbulent K-Omega	3.96×10^3	6.1
Others	1.04×10^3	1.6
Total execution time	6.49×10^4	100

Thread Number	Run Time (Sec)	Speedup
1	6.49×10^4	1
2	3.82×10^4	1.7
4	2.82×10^4	2.3
8	2.09×10^4	3.1

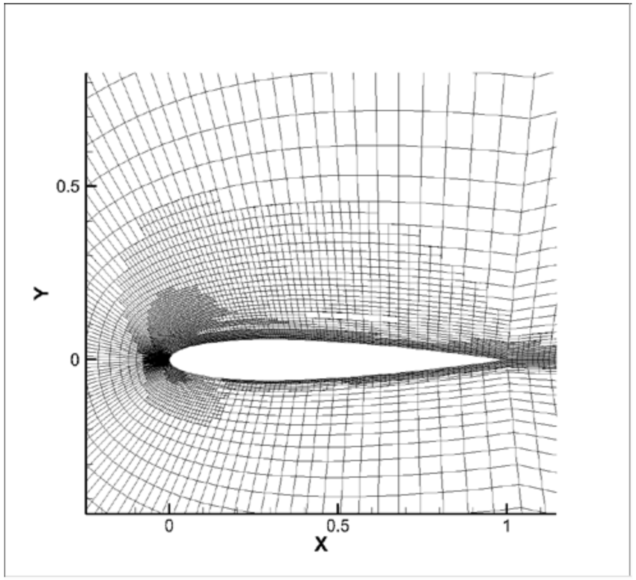
Small Desktop PC

The test machine is Dell PowerEdge R510, with two Intel® Xeon® X5672 3.20GHz processors, 128GB memory



Parallel *hp-a*daptive PCS FEM – OpenMP

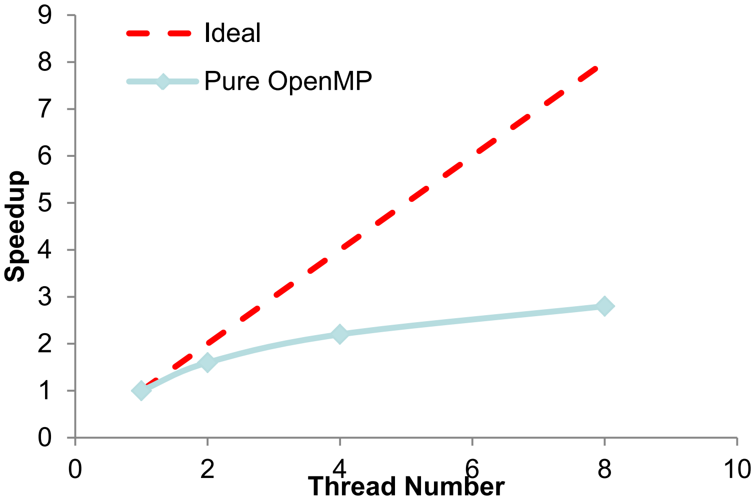
The tested case is NACA 0012 Airfoil
Mach number 0.5, attack angle 4 degree.
The mesh has 13254 elements, 13112 vertex nodes, 47162 high order nodes, and 34319 total DOF.



Thread Number	Run Time (Sec)	Speedup
1	32461	1
2	20288	1.6
4	14755	2.2
8	11593	2.8

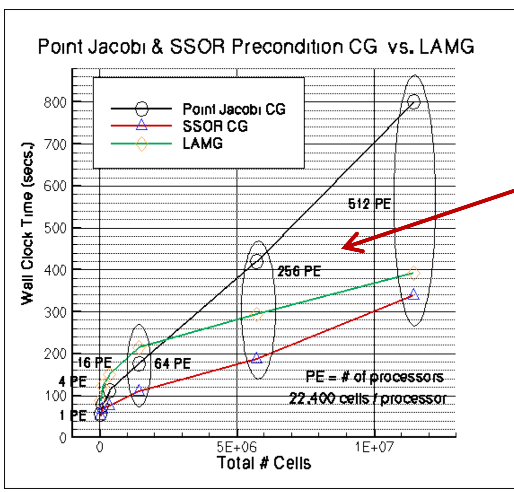
Small Desktop PC

The test machine is Dell PowerEdge R510, with two Intel® Xeon® X5672 3.20GHz processors, 128GB memory



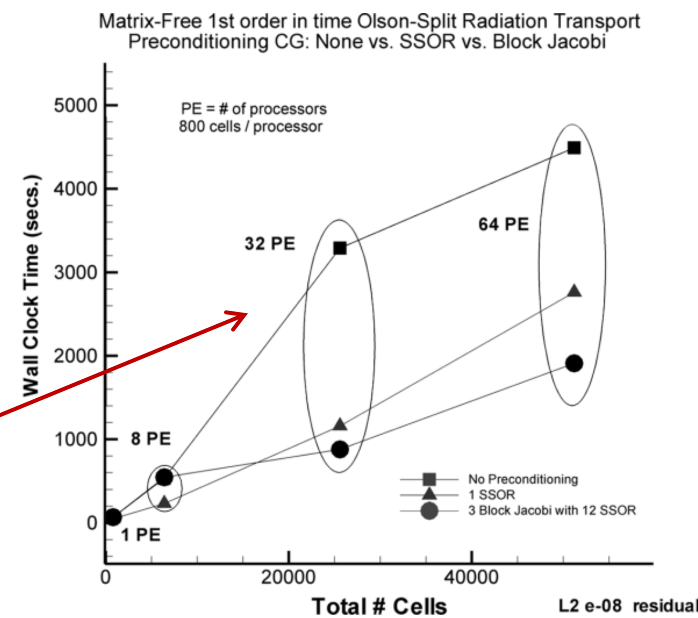
Parallel *hp-a*daptive PCS FEM – Hybrid OpenMP and MPI

- Next step - mixing OpenMP / MPI version of the code
  - Outer level has the flow domain decomposed
    - Multiple MPI processes - each process computing one sub-domain.
  - Inner level employs
    - MPI process having multiple OpenMP threads
    - Access to shared objects by multiple threads is coordinated via OpenMP synchronizations.
  - Data exchange across sub-domains with MPI
  - Based on our MPI codes: KIVA-4mpi and Zathras P1 radiation transport
- Linear equation solver system is already MPI Capable
  - Pressure solve example with MPI
    - Our linear equation solver and PCG package (Joubert and Carey) using CG solve and in-situ preconditioning of
      - Point Jacobi, SSOR and Block Jacobi
      - LAMG (Los Alamos Multigrid)



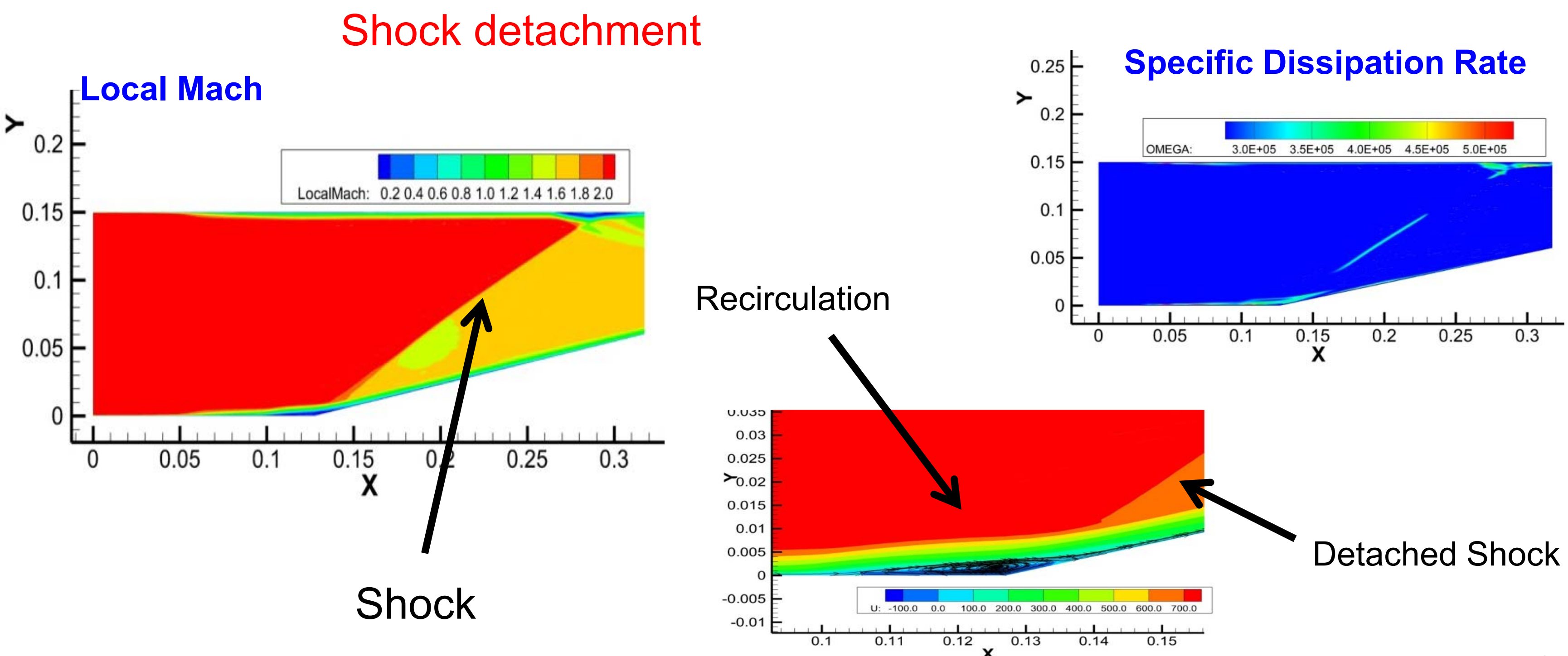
Larger Cluster

Small Cluster



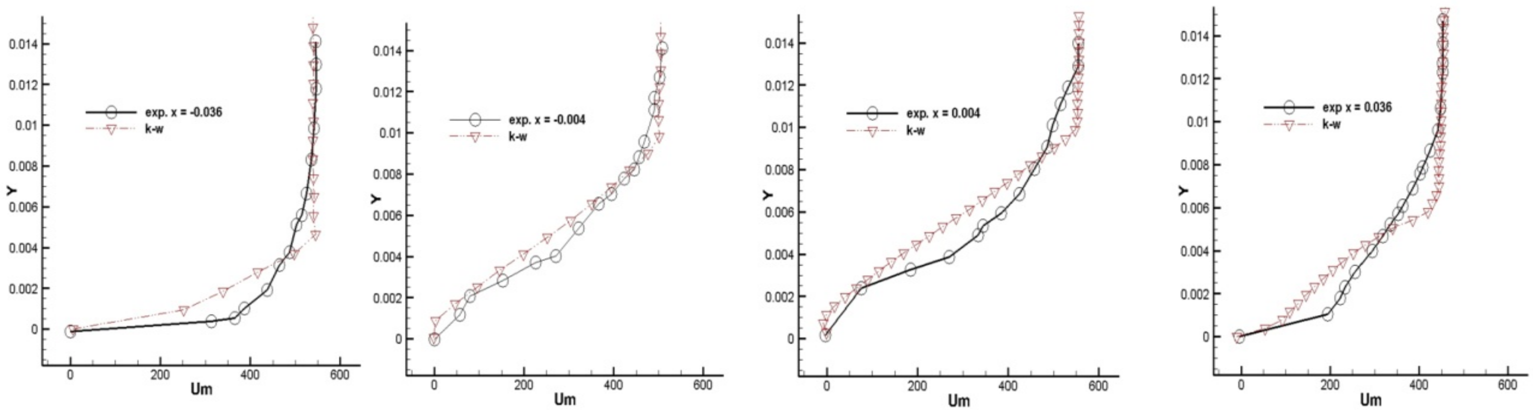
k-ω V&V - Viscous Flow on 18^o Compression Ramp

- 18^o compression ramp inlet speed Mach = 2.25
- *h*-adaptive turbulent (*k-ω*) PCS FEM (2 levels tracking the shock front in time).
- Boundary layer separation, shock detachment and flow reversal (recirculation) in agreement experiment and other solutions.
- Wall-law is **not** applicable from transonic to hypersonic regimes
    - model must handle near wall field without wall-law (not k-ε)



V&V - Viscous Flow on 18º Compression Ramp

- 18º compression ramp inlet speed Mach = 2.25
- *h*-adaptive turbulent (*k-ω*) PCS FEM (3 levels tracking the shock front in time).
- Integrate to wall – can do with k-ω, **can't do** **with k-ε**

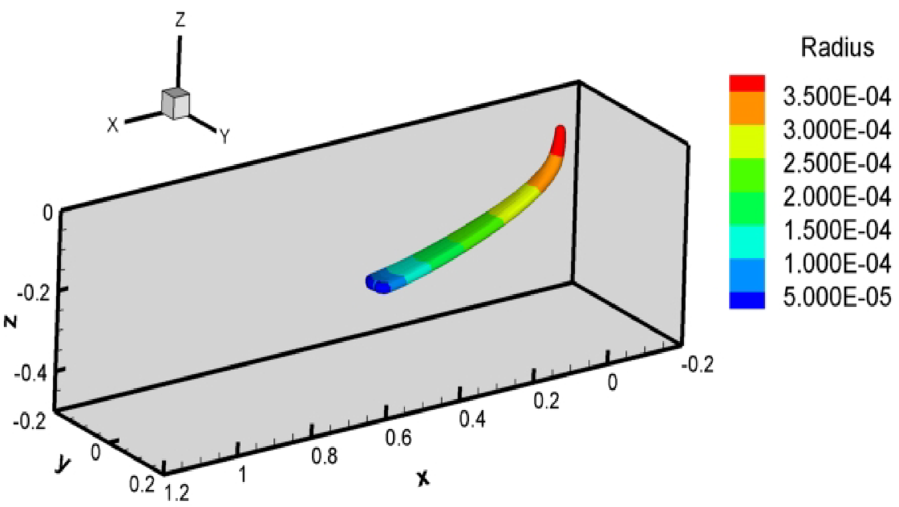


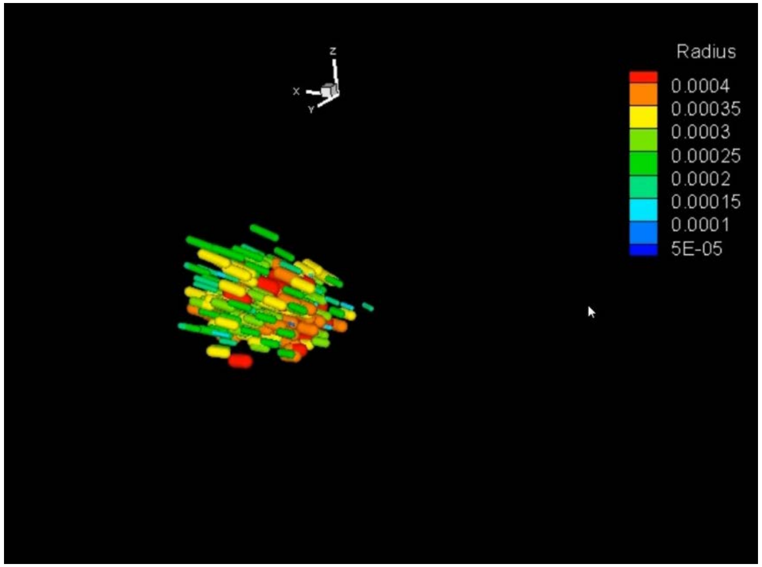
a) b) c) d)

U (mean velocity) in bottom boundary layer using k-ω 2-equation model.
Comparison to data at various locations:
u upstream(-) and downstream(+) of the ramp a) -0.032m , b) -0.004m, c) +0.004m, and d) +0.032m.

KIVA Multi-component Injection and Spray in FEM

- **Improving the current algorithms with FEM**
- **KIVA multi-component spray with collision, break-up, evaporation, wall-film, & splash models have:**
  - Increased robustness on FEM
    - Exact location found quickly, robustly.
  - Precisely locating particles and associated flow/fluid properties >= 2nd order spatial accuracy.
    - Fluid properties are exactly transferred to the injection spray – grid scale accuracy to subgrid (grid convergent).





KIVA Spray, Chemistry & Spark ignition in PCS FEM system

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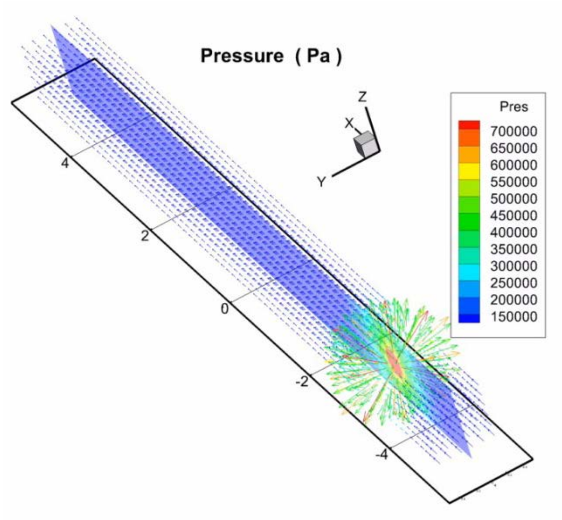
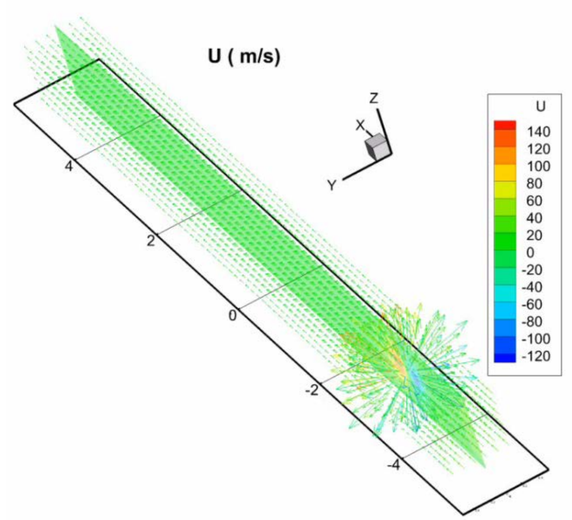
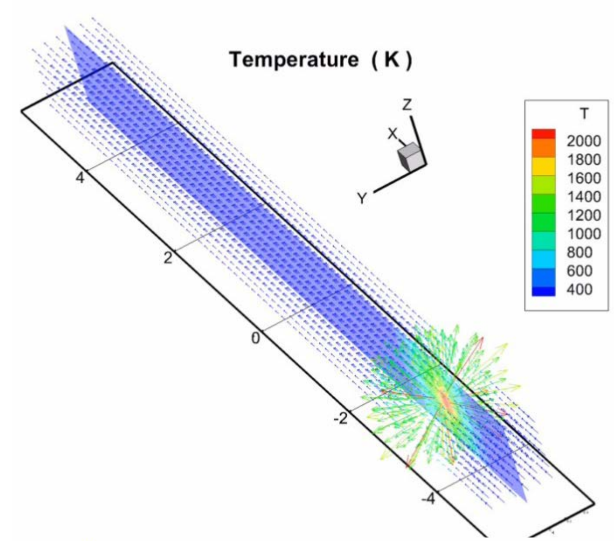
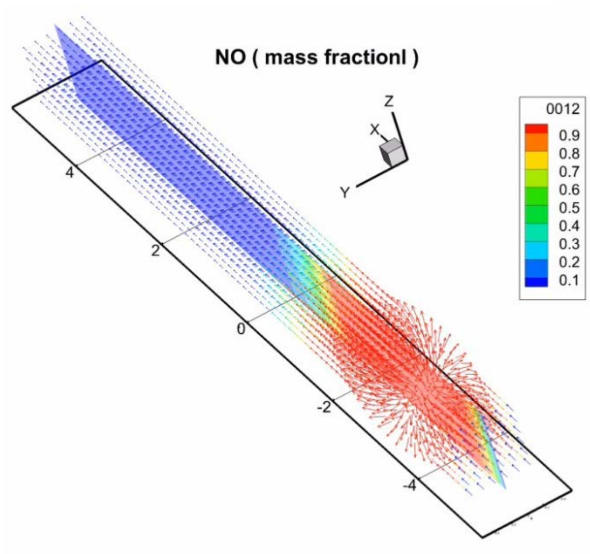
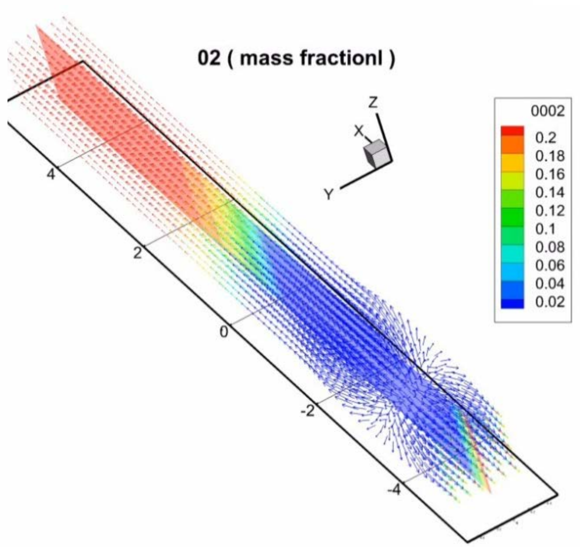
Spark Ignition of Injected Gasoline

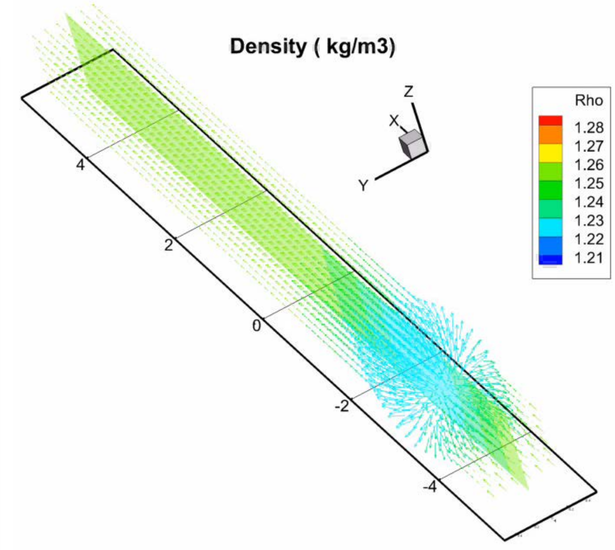










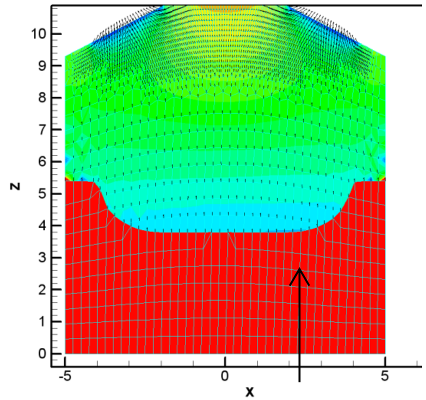


Developing Duct Flow
Mach 0.08

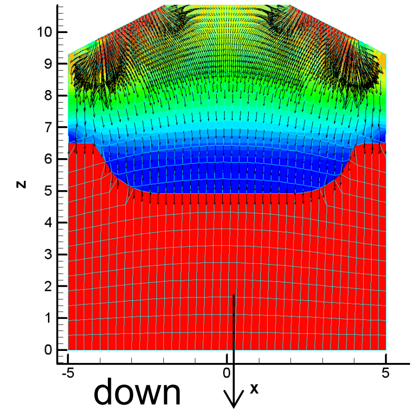
Local ALE for moving parts on unstructured grids

- ***New* local ALE FEM**
  - ***Not often in CFD we even get a win-win situation***
  - Increase robustness and is 2^{nd} order accurate.
  - Simulations with higher resolution.
  - Use of overset parts/grids.
  - Grid is of body only, fluid only.
  - Allows for automatic grid generation by Cubit or ICEM
    - CAD to Engine Grid!

2-D engine type test of ALE

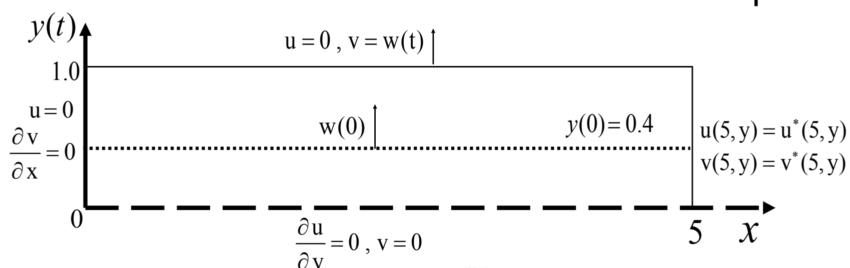


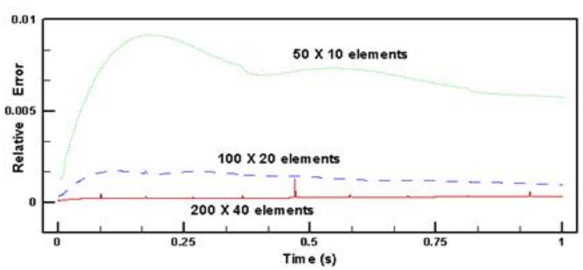
up

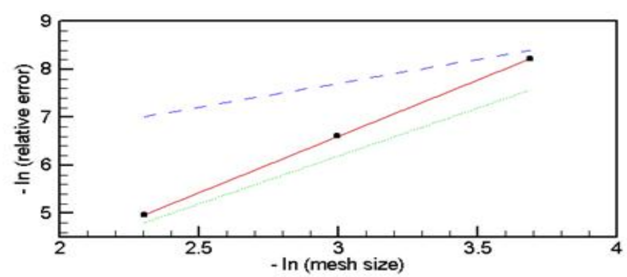


down

Test Case: Layer of fluid between two plates separating with speed w(t). Height goes from y = 0.4 to 1.0; (u*, v*) is the analytical solution.



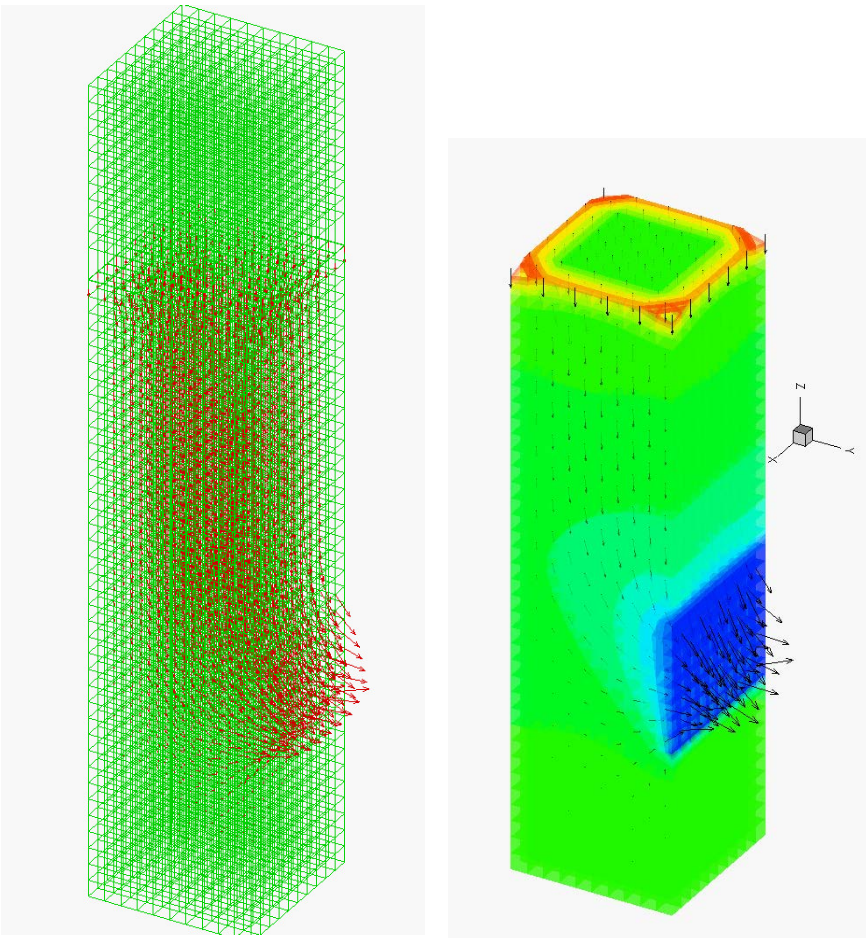




Grid convergence test : Average relative error vs. analytic solution to 2d pump(function of time) and having of 2^{nd} order spatial accuracy.

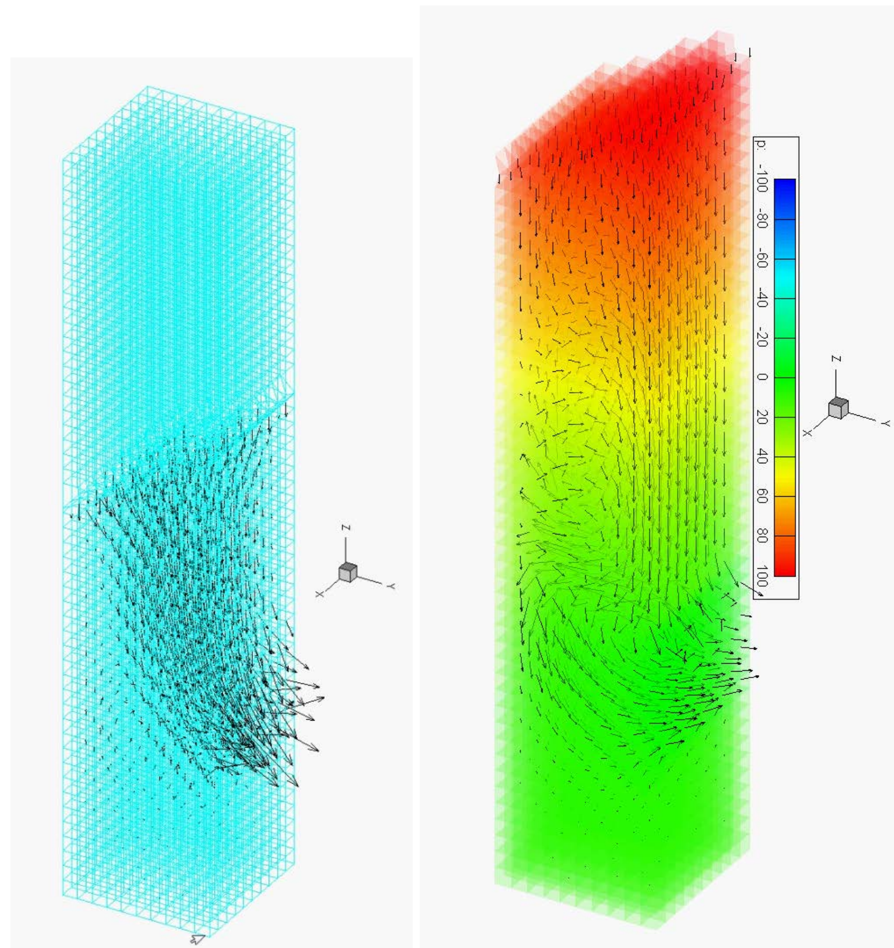
Local 3-D ALE for moving parts on unstructured grids

- Local 3-D local ALE for moving parts on unstructured grids
  - New prism element required



Flat piston surface, perpendicular to grid planes

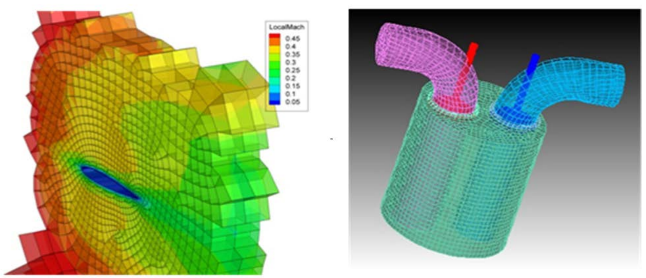
Slanted piston surface, 30^{o} to side walls



Grid Generation – Cubit and MeshTool

- Overlaying parts for easy/automatic grid generation.
  - Cubit or MeshTool for unstructured hexahedral grids for engine domains.
  - New Local ALE method allows for:
    - Overset grid generation possible – fast CAD to CFD grid
    - Robust moving parts
    - Accurate moving parts representation

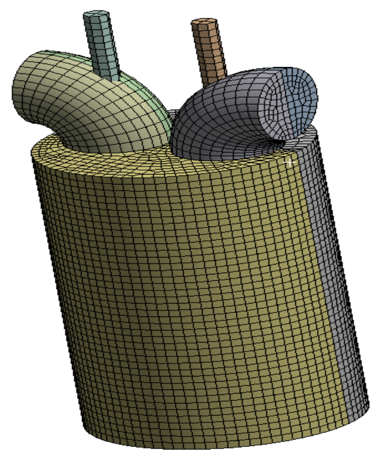
FEM PCS Grids

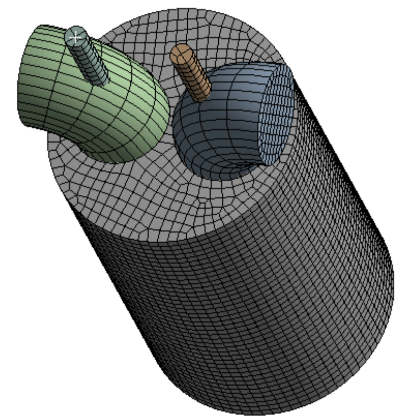


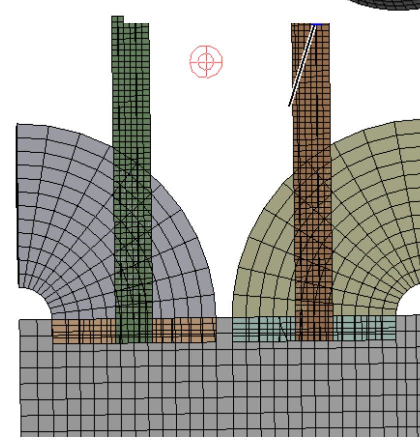
a) 3-D NACA Airfoil b) Engine grid

Cubit generated grid

MeshTool generated grid







Manpower time - 2 minutes

Program Collaborators

- Purdue, Calumet
  - *hp*-Adaptive FEM with Predictor-Corrector Split (PCS)
  - OpenMP and MPI
  - Turbulence modeling
    - Xiuling Wang and GRA
- University of New Mexico
  - Moving Immersed Body
  - Boundaries Algorithm Development
    - Juan Heinrich Monayem Mazumder (PostDoc) and GRA
- University of Nevada, Las Vegas
  - Hybrid RANS-LES
    - Darrell Pepper and GRA
- LANL
  - PCS FEM
  - Adaptive methods,
  - turbulence and spray modeling, chemistry models and grid incorporation.
    - David Carrington and 3 @¼ time GRA's total over FY 11/12/13

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Future or Ongoing effort in FY13 to FY 14 Parallel hp-adaptive PCS FEM with 3d

- Parallel *hp*-adaptive PCS FEM in 3-D
  - OpenMP embedded in MPI Parallel constructions
    - Continuing MPI, enhanced by OpenMP
    - matrix solver already developed for massively parallel constructions.
- Local ALE in 3-D
  - Local 2-D completed and V&V!
- LES development (as a template for others at least)
- Other turbulence closure
  - Turbulence modeling (Reynolds Stress Modeling - moment methods)
- **Spray model development in FEM**
  - Use phase space information from fine grain solutions of injector.
  - New algorithms, Volume of Fluid interface tracking (VOF)
- Test cases: more testing and comparison to experiment
  - Perform more rigorous comparisons to data and analytics.
    - Chemistry, Injection, Local ALE, Fluid dynamics, Turbulence, etc.…
  - Publish results in peer reviewed articles (3 papers just recently).

Summary

- **Accurate, Robust and well Documented algorithms**
  - Developing and implementing robust and extremely accurate algorithms – Predictor-Corrector *hp-adaptive* FEM.
    - Reducing model's physical and numerical assumptions.
    - Measure of solution error
    - Drives the resolution when and where required.
    - New algorithm requiring less communication
    - no pressure iteration, an option for explicit: newest architectures providing super-linear scaling.
    - Robust and accurate immersed moving parts algorithm (local ALE).
      - 2d completed
      - 3d under development.
  - Conjugate Heat Transfer
    - More accurate prediction in wall film and its effects on combustion and emissions under PCCI conditions with strong wall impingement.
  - Validation in progress for all flow regimes
    - With Multi-Species
    - Beginning spray and chemistry model incorporation.
- **Grid generation**
  - Quickly generate grids from CAD surfaces of complex domains.
    - Cubit Grid interface developed.
    - Cubit supplies rapid generation, from quickly developed scripts.
      - The scripts are the technology now developed which can be easily modified for various engine designs.

Technical Back-Up Slides

(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

Fractional Step or Velocity Predictor Corrector Petrov-Galerkin formulation

- FEM Discretization for PCS
  - Velocity predictor

$$\left\{\Delta \mathbf{U}_i^*\right\} = -\Delta t\left[\mathbf{M}_v^{-1}\right]\left[\left[\mathbf{A}_u\right]\left\{\mathbf{U}_i\right\} + \left[\mathbf{K}_{\tau u}\right]\left\{\mathbf{U}_i\right\} - \left\{\mathbf{F}_{v_i}\right\} - \frac{\Delta t}{2}\left(\left[\mathbf{K}_{char}\right]\left\{\mathbf{U}_i\right\} - \left\{\mathbf{F}_{char_i}\right\}\right)\right]^n$$

where $\left\{\Delta U_i^*\right\} = \left\{U_i^*\right\} - \left\{U_i^n\right\}$

  - Velocity corrector (*desire this*)

$U^{n+1} - U^* = \Delta t \dfrac{\partial P'}{\partial x_i}$ and $\left\{U_i^*\right\}$ is an intermediate

  - How do we arrive at a corrector preserving mass/continuity?
    - Continuity

$$\frac{\partial \rho}{\partial t} = -\frac{\partial \rho u_i}{\partial x_i} = -\frac{\partial U_i}{\partial x_i} \qquad \frac{\rho^{n+1} - \rho^n}{\Delta t} = -\frac{\partial U'_i}{\partial x_i}$$

Define $U' = \theta_1 U^{n+1} + \left(1-\theta_1\right)U^n$ with a level of implicitness

Desire $U^{n+1} - U^* = \Delta t \dfrac{\partial P'}{\partial x_i}$ Let $U'_i = \theta_1\left(-\Delta t \dfrac{\partial P'}{\partial x_i} + U_i^*\right) + \left(1-\theta_1\right)U_i^n$

Then $$\frac{1}{c^2}\Delta P = \Delta\rho = -\Delta t \frac{\partial U'_i}{\partial x_i} = -\Delta t \frac{\partial}{\partial x_i}\left[\left(\theta_1\left(-\Delta t\right)\frac{\partial P'}{\partial x_i} + \theta_1 U_i^*\right) + \left(1-\theta_1\right)U_i^n\right]$$

Pressure or Density Solve
Mass conserving Projection Method

So $$\frac{1}{c^2}\Delta P = \Delta\rho = -\Delta t\frac{\partial U_i^{'}}{\partial x_i} = \left[\left(\Delta t^2\theta_1\frac{\partial^2 P^{'}}{\partial x_i^2} - \Delta t\theta_1\frac{\partial U_i^*}{\partial x_i}\right) - \Delta t\left(1-\theta_1\right)\frac{\partial U_i^n}{\partial x_i}\right]$$

Let $P^{'} = \theta_2 P^{n+1} + (1-\theta_2)P^n$ with some level of implicitness

recall $$\Delta U^* = U^* - U^n$$

Then $$\frac{1}{c^2}\Delta P = \Delta\rho = -\Delta t\frac{\partial U_i^{'}}{\partial x_i} = \Delta t^2\theta_1\left(\theta_2\frac{\partial^2 P^{n+1}}{\partial x_i^2} + \left(1-\theta_2\right)\frac{\partial^2 P^n}{\partial x_i^2}\right) - \Delta t\left(\theta_1\frac{\partial\Delta U_i^*}{\partial x_i} + \frac{\partial U_i^n}{\partial x_i}\right)$$

and $\Delta P = P^{n+1} - P^n$

Density then $$\Delta\rho - \theta_2\frac{\partial^2\Delta P}{\partial x_i^2} = \frac{1}{c^2}\Delta P - \theta_1\theta_2\frac{\partial^2\Delta P}{\partial x_i^2} = \Delta t^2\theta_1\frac{\partial^2 P^n}{\partial x_i^2} - \Delta t\left(\theta_1\frac{\partial\Delta U_i^*}{\partial x_i} + \frac{\partial U_i^n}{\partial x_i}\right)$$

FEM Matrix form $$\left(\left[\mathbf{M}_p\right] + \Delta t^2 c^2\theta_1\theta_2\mathbf{H}\right)\left\{\Delta\rho_i\right\} = \left(\left[\frac{\mathbf{M}_p}{c^2}\right] + \Delta t^2\theta_1\theta_2\mathbf{H}\right)\left\{\Delta P_i\right\} =$$

$$\Delta t^2\theta_1\mathbf{H}\left\{P_i^n\right\} - \Delta t\left(\theta_1\mathbf{G}\left\{\Delta\mathbf{U}_i^*\right\} + \mathbf{G}\left\{\mathbf{U}_i^n\right\}\right) - \Delta t\left\{\mathbf{F}_{P_i}\right\}$$

Momentum/Velocity Corrector

Now $$P^{n+1} = \Delta P + P^n$$

recall $$P^{'} = \theta_2 P^{n+1} + (1-\theta_2)P^n = \theta_2 \Delta P + P^n$$

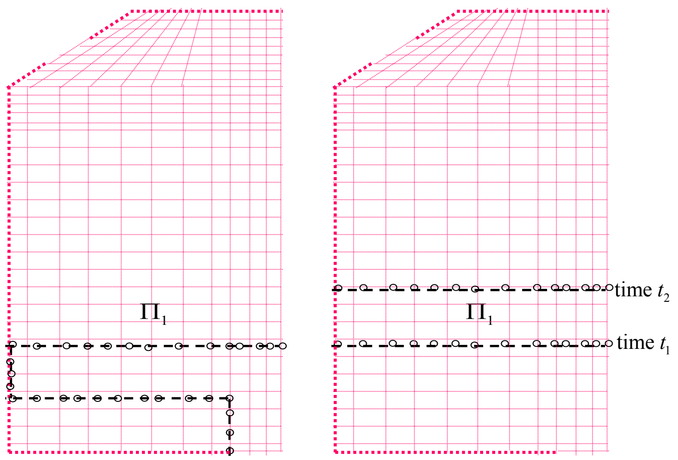
Then $$\Delta U_i = U^{n+1} - U^n = \Delta U * - \Delta t \frac{\partial P^{'}}{\partial x_i} = \Delta U * - \Delta t \left(\theta_2 \frac{\partial \Delta P}{\partial x_i} + \frac{\partial P^n}{\partial x_i} \right)$$

FEM Matrix form $$\left\{ \Delta \mathbf{U}_i \right\} = \left\{ \Delta \mathbf{U}^* \right\} - \Delta t \left[\mathbf{M}_u^{-1} \right] \left(\theta_2 \left[\mathbf{G} \right] \left\{ \Delta p_i \right\} + \left[\mathbf{G} \right] \left\{ p_i^{\,n} \right\} \right)$$

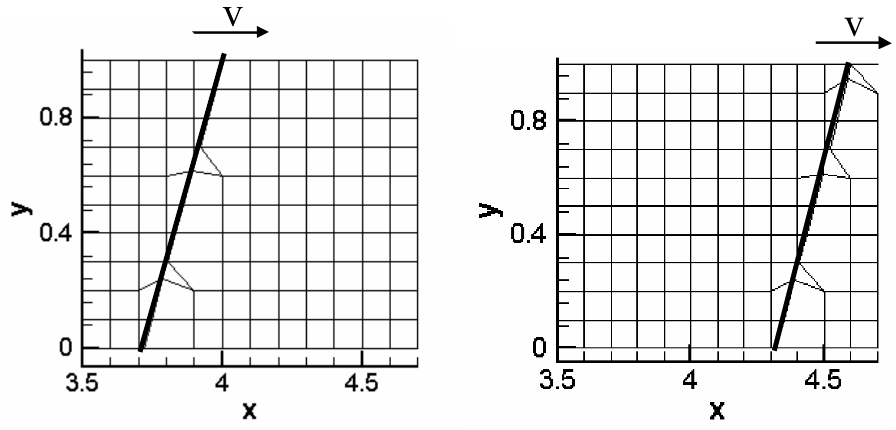
where $$\left\{ \mathbf{U}_i^{\,n+1} \right\} = \left\{ \Delta \mathbf{U}_i \right\} + \left\{ \mathbf{U}_i^{\,n} \right\}$$

final mass conserving velocity $$u^{n+1} = U^{n+1} / \rho^{n+1}$$

Local ALE Method for Flow Calculations in Physical Domains Containing Moving Interfaces



a b



a b

- Possible markers describing piston
  - 28 markers and at every time step (a)
  - At least one marker in element partially occupied by the piston.
- Computational region is domain lying above the piston
  - Suffices to define the upper interface
  - 14 markers lying in the upper surface (b)

- Slanted piston interface depicted
  - the thicker dark line
  - moving from left to right,
  - the computational domain:
  - to the left of the piston interface:
    - a) Initial mesh at time t = 0;
    - b) mesh at a later time t = 1