A SCALABLE SOFTWARE FRAMEWORK FOR THERMAL RADIATION ANALYSIS

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Abstract

A parallel scalable software framework built to conduct fluid-thermal radiation analysis.

- Solution of the energy balance governed by convection, radiation, conduction and fluxes that are highly dependent on the environmental conditions.
- Implementation of the Finite Element Method to solve governing transport equations
- Radiation heat transfer solved as an all to all connection represented as a dense radiosity matrix
- Simulation combines solution of dense matrices for radiation exchange and sparse matrices for transport equations
- Simulations are done on multi-core + GPU's supercomputers, Kraken and Keeneland

Governing Equations

Conservation of Energy within a control volume and across the boundaries.

$$DE: \quad Ł(T) = \frac{\partial}{\partial t}(\rho C_p T) + \nabla(-k\nabla T) - s = 0 \quad on \quad \Omega$$

$$BCs: \quad \ell(T) = k\nabla T \bullet n + h(T - T_\infty) + \varepsilon\sigma(T^4 - T_r^4) + f(t) = 0 \quad on \quad \partial\Omega$$

Physical considerations

Conduction Conducted on 2D sheet bodies in 3D space. Dictated by thermal diffusivity (k) of the conducting material.

Convection Coefficient (h) governed by Grashoff Number (Gr) for natural convection and the Prandtl Number (Pr) for forced convection. Prandtl number is dictated by the surface velocity generated.

Forced (U>0) $h = (C_1 k Pr^{1/3} Re^{1/2})/k$

Natural (U~0) $h = kC_2(Gr * Pr)^n$

Solar Flux The solar flux takes into account the effects of short-wave thermal, Planckian and specular-diffuse radiation. Values are correlated to lookup tabels generated from experimental data

Radiosity Radiosity is governed by the surface temperature, surface to surface view factors and the emmisivity (ϵ) of the surface.

Radiosity Formulation

The Finite Element Method is extended to the formulation of the radiosity solution. The radiosity is the total radiation intensity leaving a surface and is dependent on all other surfaces in the system.

$$R_i = \varepsilon_i \sigma T_i + \rho_i \sum_{k=1}^{n} VF_{i\to k} R_k$$

The Galerkin weak statement is used to transform the radiosity energy balance into an integral form.

$$\{GWS\}_{e=i} = \int_{\Omega_i} \{N\} \begin{bmatrix} \left(\{N\}^T\{R\}_i - \varepsilon_i\sigma\{N\}^T\{T^4\}_i\right) dA_i \\ -\rho_i \sum_{k=1}^{n} VF_{i\to k}\{N\}^T\{R\}_k dA_i \end{bmatrix} = \{0\}$$

Transformation of the GWS to the element matrix form gives the following algebraic expression.

$$\frac{1}{\rho_i} det_i\,[MASS]\,\{R\}_i - \sum_{k=1}^{n} VF_{i\to k} det_i\,[MONE]\{R\}_k = \frac{\varepsilon_i\sigma}{\rho_i} det_i\,[MASS]\,\{T^4\}_i$$

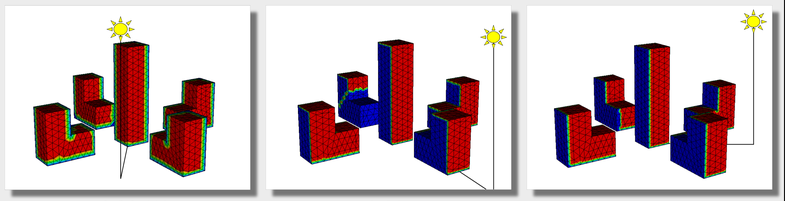
Assembly of the radiosity formulation into a hyper-matrix allows for solution of a dense matrix using cuBLAS libraries.

Sun Visibility

Visibility generated for solar flux BC

- Projects all vertices onto plane orthogonal to sunlight.
- For each vertex check which elements enclose the vertex
- For each possible obstruction calculate whether object lies in front or behind vertex and returns TRUE/FALSE value
- Parallel capable algorithm (in development)
  - Number of surfaces N
  - Number of obstructions M
  - Algorithm = O(M*N) where M < N

Sun Visibility test on multiple objects with obstruction (red denotes visibility)



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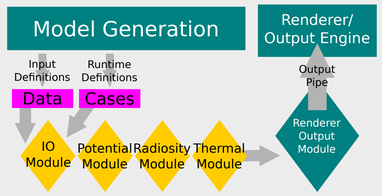
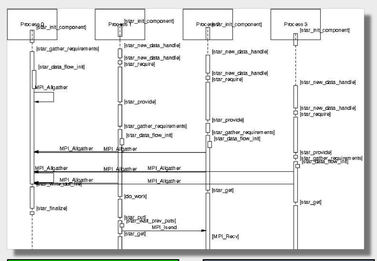
Software Framework

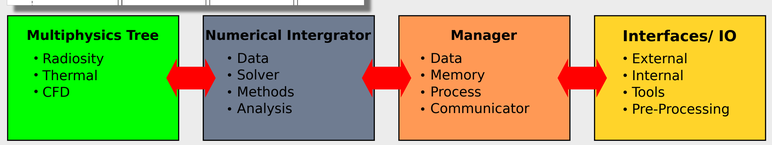
Multi module support for additional fexibility in physics



Work Flow Dagram for multi-modular simulation test case

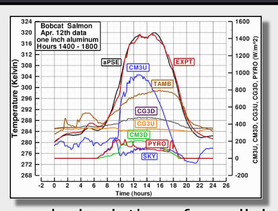


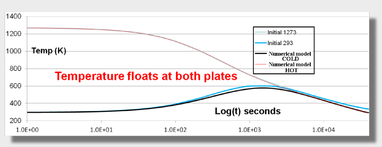
- **IO**
  - Visit - Data postprocesing
  - Cubit - Mesh Generation
  - Tecplot - Output file format
  - Metis - Parallel partioner
  - Patran - ASCII input format
  - HDF5 - Binary input format
- **Thermal**
  - Trilinos - Sparse matrix sorver
- **Fluid Flow**
  - Trilinos - Sparse Matrix Solver
- **Radiosity**
  - View3D - Parallelized view factor calculation
  - SunVis - Sun position and visibility
  - Magma - GPU linear solver
  - Scalapack - multicore + multi GPU linear solver



Benchmark Validation

- 24 hour experiment provides data correlation for solar flux on surface of flat plate
- Data from single plate used in computing thermal distribution on two parallel plates

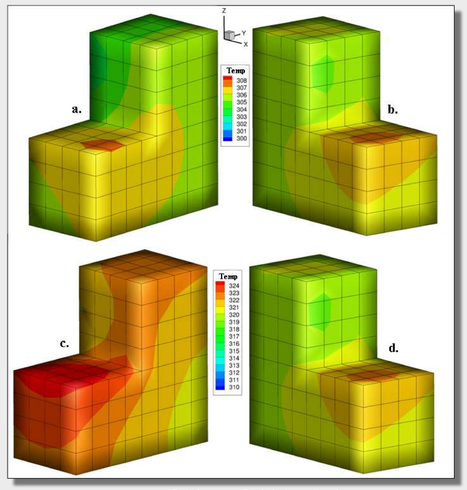




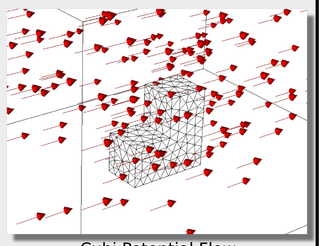
- Numerical solution of parallel plates closely matches experimental results giving validation to solar flux inclusion

Test Cases

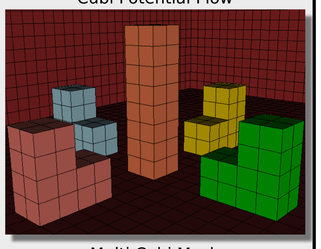
- Test Cases
  - Single Cubi - Focus on diffusion, simple radiation and solar flux
  - Multiple Cubi - Introduces obstruction to radiosity and solar flux
  - SUV - Complex geometry, substantial mesh size and multiple material properties



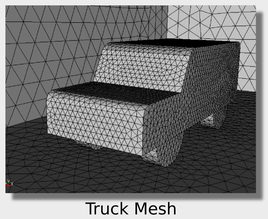
24 hour Cubi Analysis



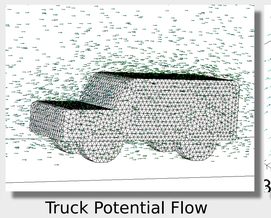
Cubi Potential Flow



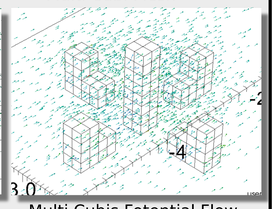
Multi Cubi Mesh



Truck Mesh



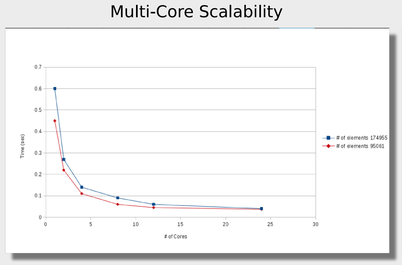
Truck Potential Flow



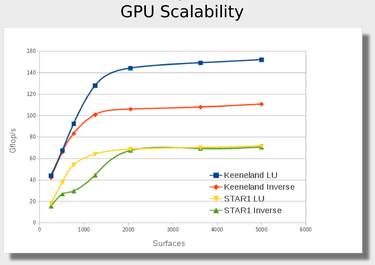
Multi Cubis Fotential Flow

Performance

Thermal Module
Multi-Core Scalability

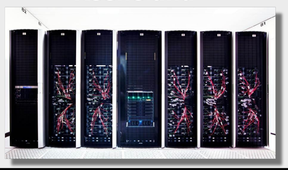


Radiosity Module
GPU Scalability

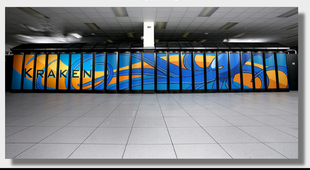


Computing Platform

Keeneland



Kraken



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