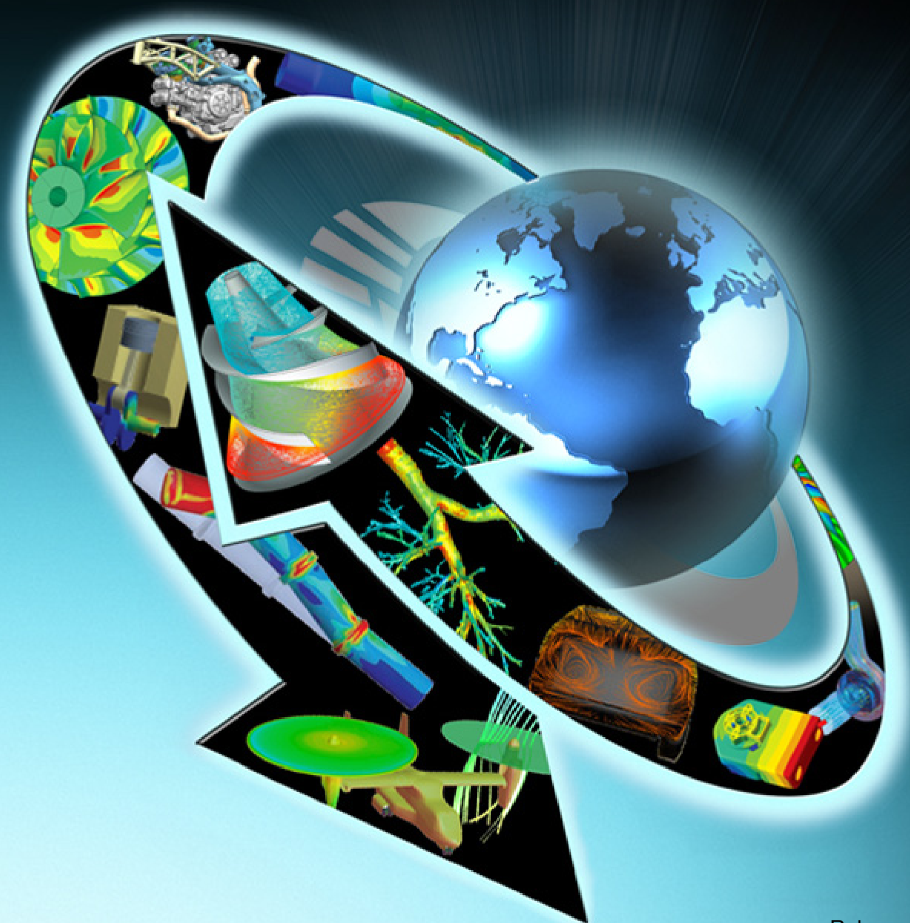
Customer Training Material

Lecture 2

Conduction Heat Transfer



Heat Transfer Modeling using ANSYS FLUENT

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Agenda

- Introduction
- Energy equation in solids
  - Equation solved in FLUENT
  - Shell conduction model
  - Non-conformal coupled wall
  - Anisotropic conductivity
- Moving solids
- Solver parameters

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Agenda

- **Introduction**
- Energy equation in solids
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Conduction Definition

- **Heat transfer is energy in transit due to a temperature difference**

- **Conduction phenomenon:**
  - **Energy is transported by basic carriers**
    - **Fluids – molecules, atoms**
    - **Solids – free electrons**

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Fourier's Law

- **Conduction heat transfer is governed by Fourier's Law.**
- **Fourier's law states that the heat transfer rate is directly proportional to the gradient of temperature.**
- **Mathematically,** $$q_{\text{conduction}} = -\underbrace{k}_{\text{Thermal conductivity}} \nabla T$$
- **The constant of proportionality is the thermal conductivity (k).**
  - **k may be a function of temperature, space, etc.**
  - **For isotropic materials, k is a constant value.**
  - **In general (for anisotropic materials), k is a matrix.**
- **Table of *k* values for various materials can be found in the Appendix**

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Energy Equation for Solid Materials

- **Equation solved in FLUENT**

$$\underbrace{\frac{\partial(\rho h)}{\partial t}}_{\text{Unsteady}} = \underbrace{\nabla \cdot (k \nabla T)}_{\substack{\text{Conduction} \\ \text{(Fourier's Law)}}} + \underbrace{S_h}_{\substack{\text{Enthalpy} \\ \text{Source}}}$$

- **The dependent variable h is the enthalpy,**

$$h = \int_0^T C_p \, dT$$

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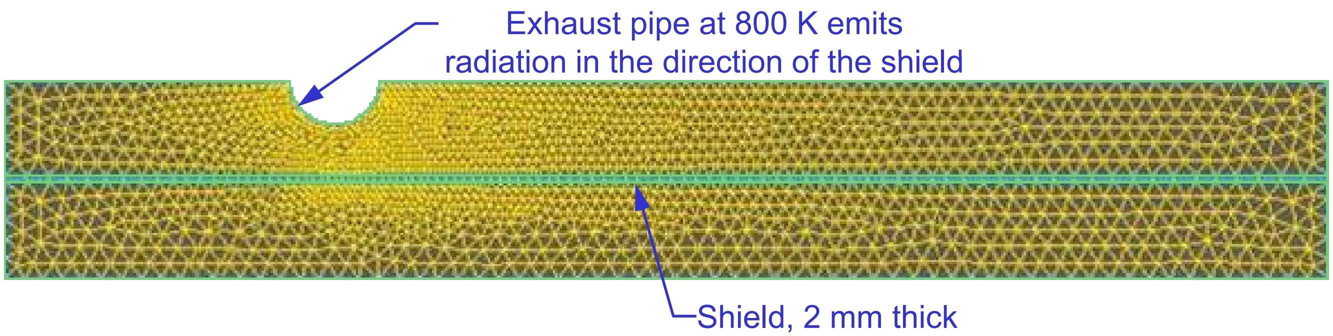
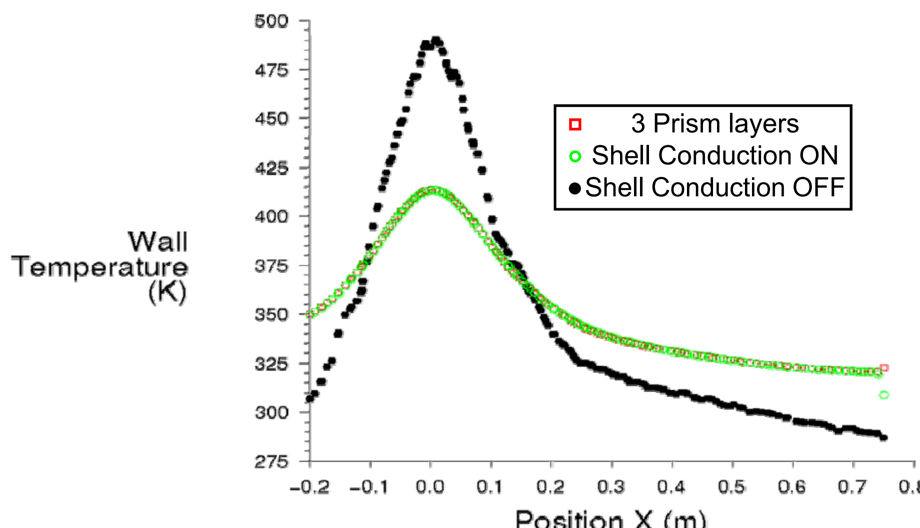
Shell Conduction

- In FLUENT, by default, planar heat transfer is ignored if the wall thickness is not meshed.



- Results from shell (1 layer) matches with that obtained using 3 prism layers

Plate Temperature
Along the Flow Direction



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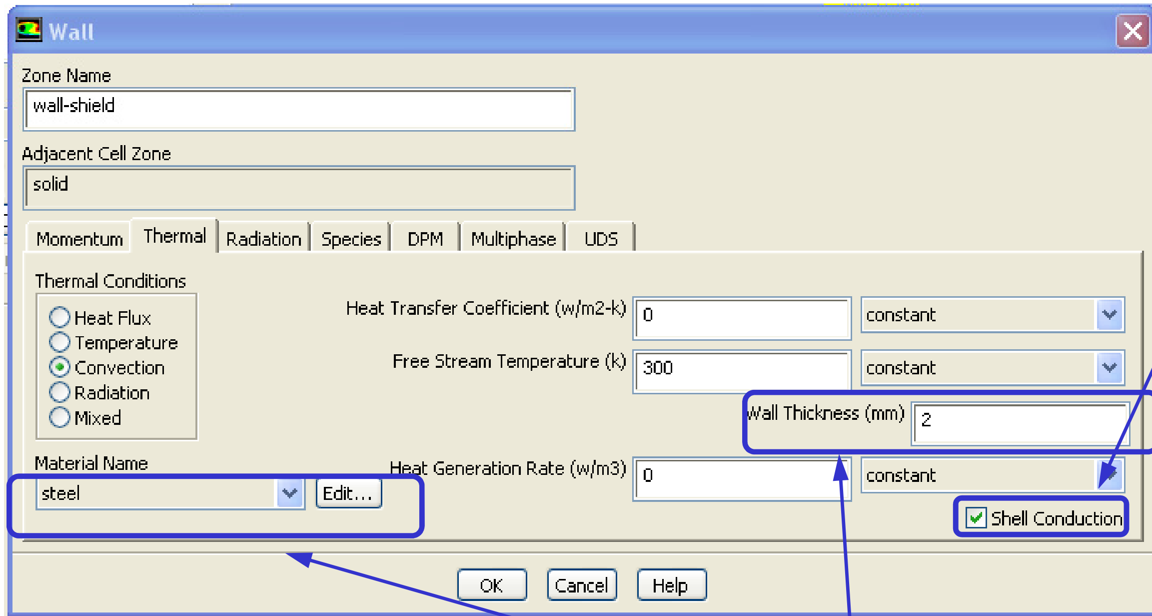
Shell Conduction

- **To activate shell conduction, select it in the wall boundary condition panel.**



Don't forget to specify the material name and wall thickness!

- **Text commands**
  - **To activate shell conduction for all walls with nonzero thickness:**
    `grid/modify-zone/create-all-shell`
  - **To deactivate all shell conduction zones:**
    `grid/modify-zone/delete-all-shell`

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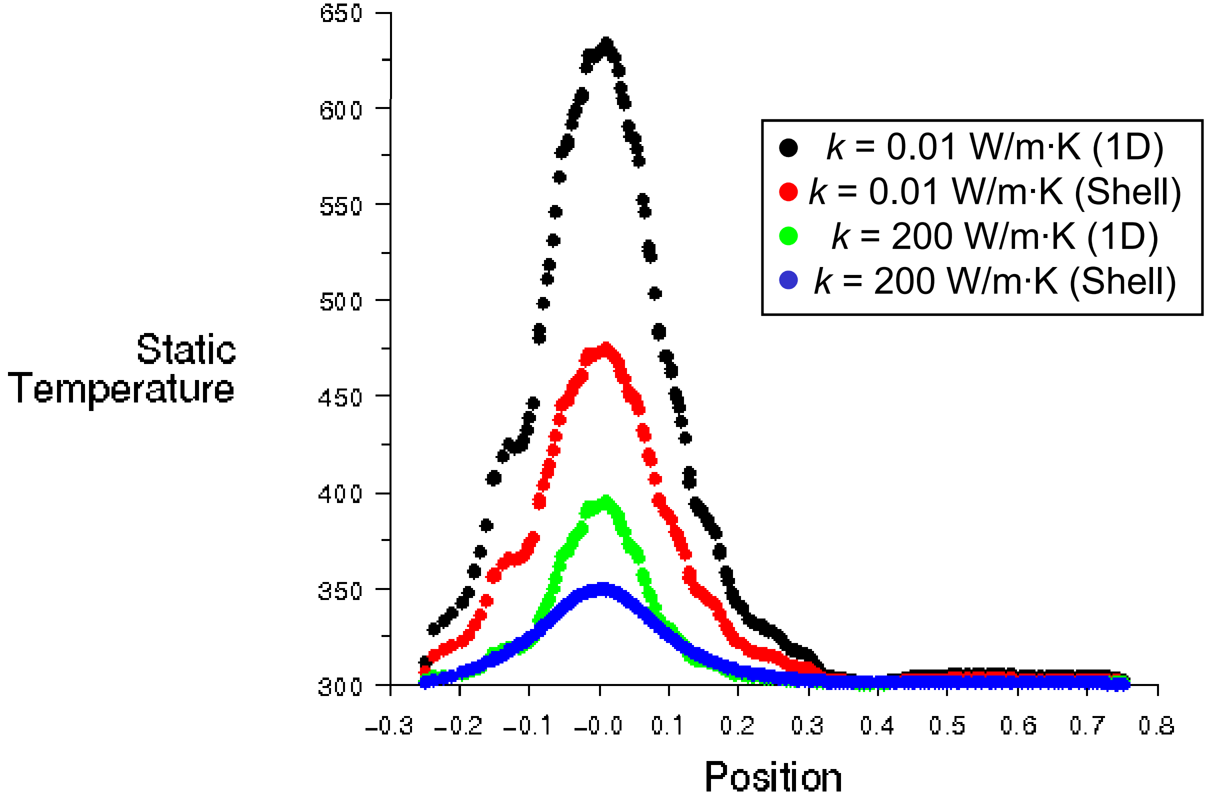
Shell Conduction

- **Shell conduction needed regardless of thermal conductivity**



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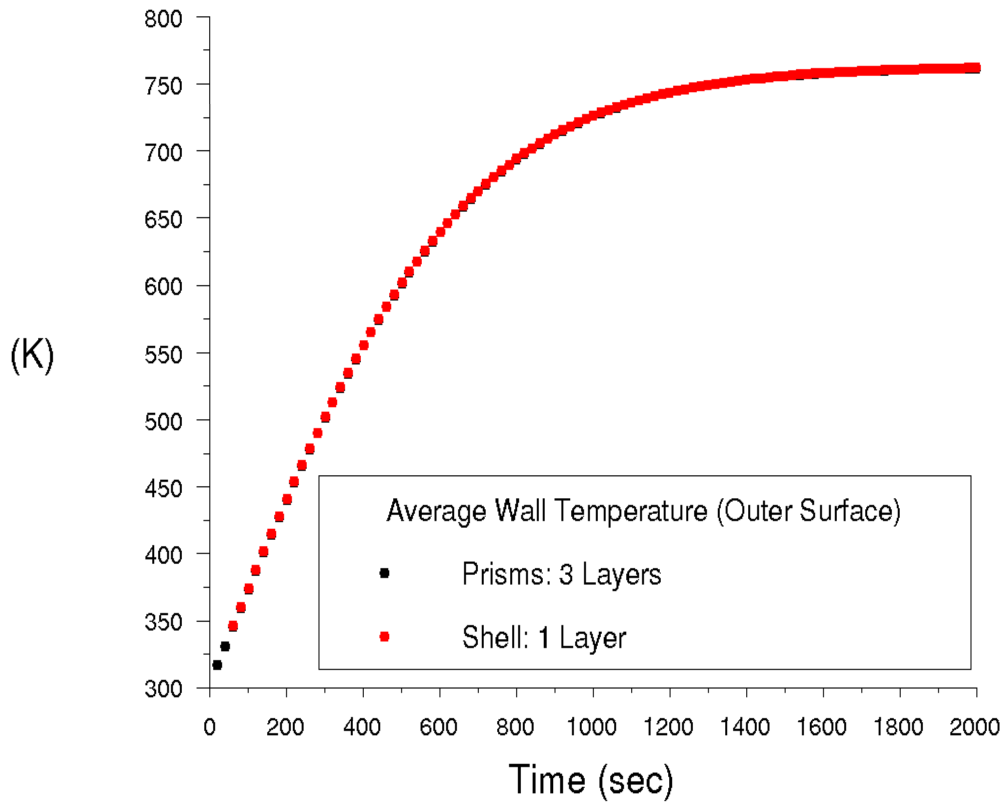
Shell Conduction – Unsteady

- **The shell conduction model takes into account thermal inertia.**



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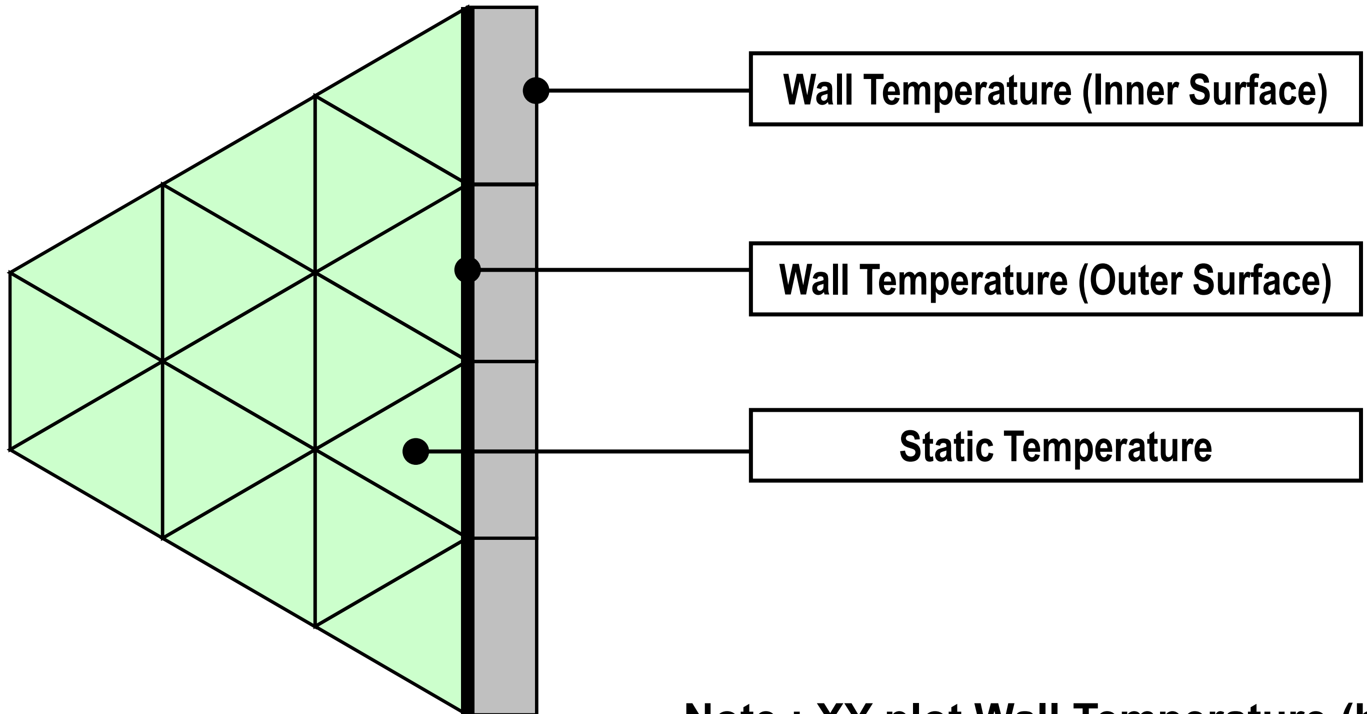
Shell Conduction – Postprocessing

- **Which temperature should we post-process on a boundary wall with shell conduction?**



Note : XY plot Wall Temperature (both inner and outer) allow use of cell values only

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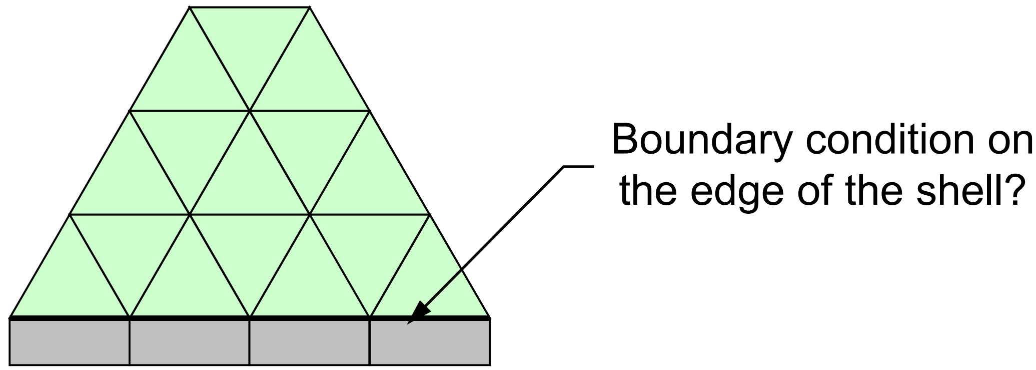
Shell Conduction – Connectivity



- **Specification of boundary condition at the wall end:**
  - **By default, wall shell is adiabatic**
  - **If shell conducting wall connects:**
    - **Another shell conducting wall – The connecting edge has a coupled boundary condition.**
    - **Another non-conducting external wall – Edge has the same thermal boundary condition.**

- **Heat flux on virtual boundaries is not reported in the total heat flux report.**

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Shell Conduction – Limitations

- **Limitations of the shell conduction model:**
  - Shells cannot be created on non-conformal interfaces.
  - Shell conduction cannot be used on moving wall zones.
  - Shell conduction cannot be used with FMG initialization.
  - Shell conduction is not available for 2D.
  - Shell conduction is available only when the pressure-based solver is used.
  - Shell conduction cannot be used with the non-premixed or partially-premixed combustion model.
  - When used in conjunction with the Discrete Ordinates (DO) radiation model, shell conducting walls cannot be semi-transparent and should not be used with the DO/Energy Coupling Method.
  - Shell conducting walls cannot be split or merged. If you need to split or merge a shell conducting wall, you will need to turn off the Shell Conduction option for the wall (in the Wall dialog box, perform the split or merge operation, and then enable Shell Conduction for the new wall zones.
  - The shell conduction model cannot be used on a wall zone that has been adapted. If you want to perform adaption elsewhere in the computational domain, be sure to use the mask register described in Section 27.11.1. This will ensure that adaption is not performed on the shell conducting wall.

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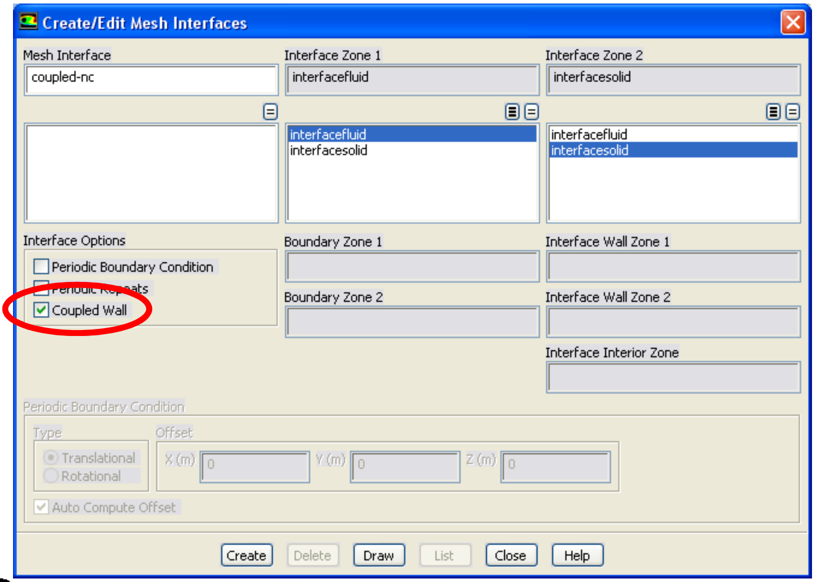
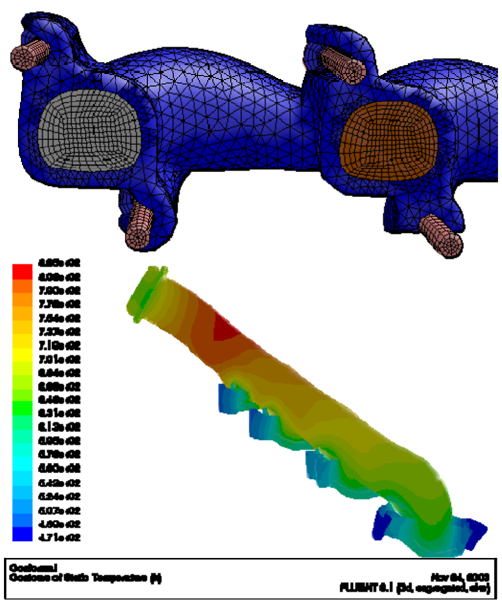
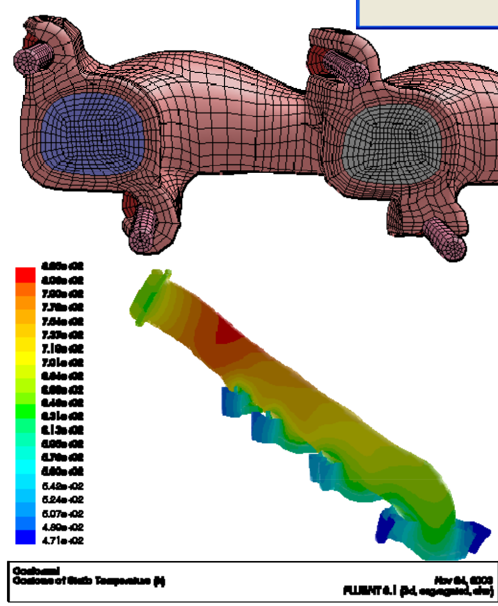
Non-Conformal Coupled Wall

- **Non-conformal coupled wall:**
  - **We can use fine mesh on fluid zone and coarser mesh on solid zone**
  - **You can also model baffles.**







Note:

Use `/display/zone-grid ID`
to display the shadow walls

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Anisotropic Thermal Conductivity

- **Anisotropic thermal conductivity is only available for solid materials.**
- **By default, the thermal conductivity is considered to be isotropic.**
- **For anisotropic materials, the thermal conductivity is a matrix.**

$$q_i = -k_{ij} \frac{\partial T}{\partial x_j}$$

- **The thermal conductivity matrix can be defined using one of five different methods:**
  - **Orthotropic**
  - **Cylindrical orthotropic**
  - **General anisotropic**
  - **Biaxial (shell conduction only)**

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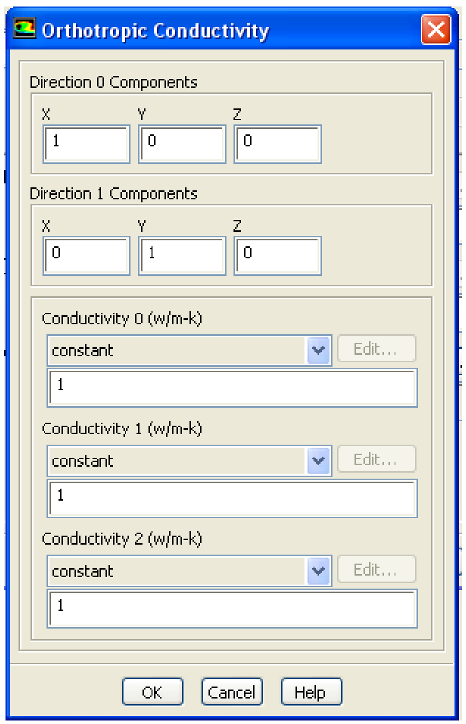
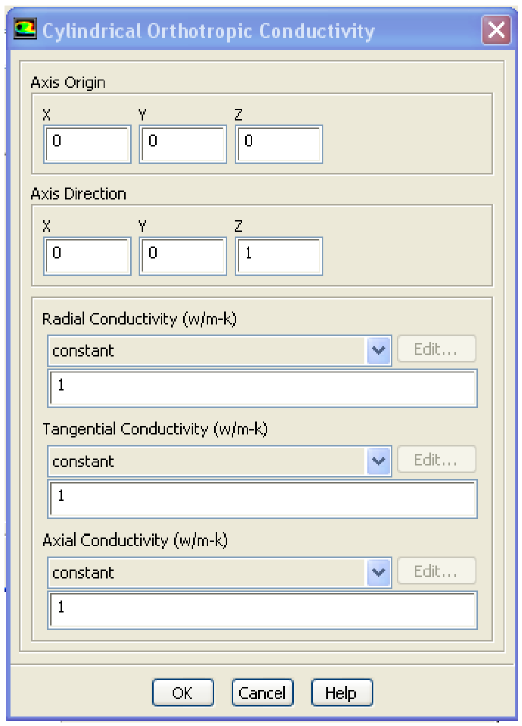
Anisotropic Thermal Conductivity for Solid Zones

- **Defining parameters may depend on temperature.**
- **UDF or constant/polynomial definition is also possible.**

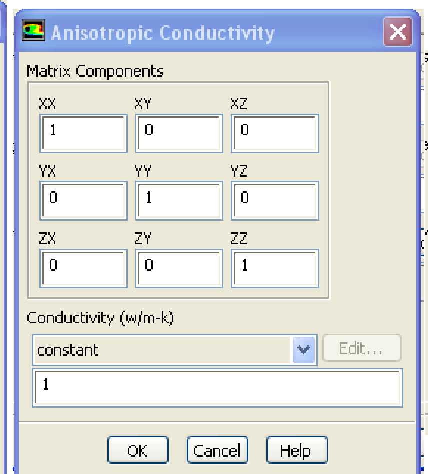
Orthotropic



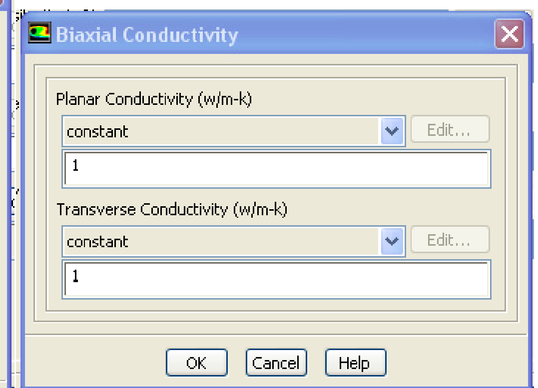
Cylindrical Orthotropic



Anisotropic



Biaxial (shell conduction only)



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  - Equation solved in FLUENT
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- **Moving solids**
- Solver parameters

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Conduction in Moving Solids

- **Equation solved in FLUENT (for moving solids) :**

$$\underbrace{\frac{\partial(\rho h)}{\partial t}}_{\text{Unsteady}} + \underbrace{(\mathbf{V}\cdot\nabla)(\rho h)}_{\text{Solid Motion}} = \underbrace{\nabla\cdot(k\,\nabla T)}_{\substack{\text{Conduction} \\ \text{(Fourier's Law)}}} + \underbrace{S_h}_{\substack{\text{Enthalpy} \\ \text{Source}}}$$

- **The convective term comes from an Eulerian description of solid motion.**

- **If the mesh moves with the solid like for sliding mesh or rigid body deforming mesh (Lagrangian representation), then the solid motion term vanishes**

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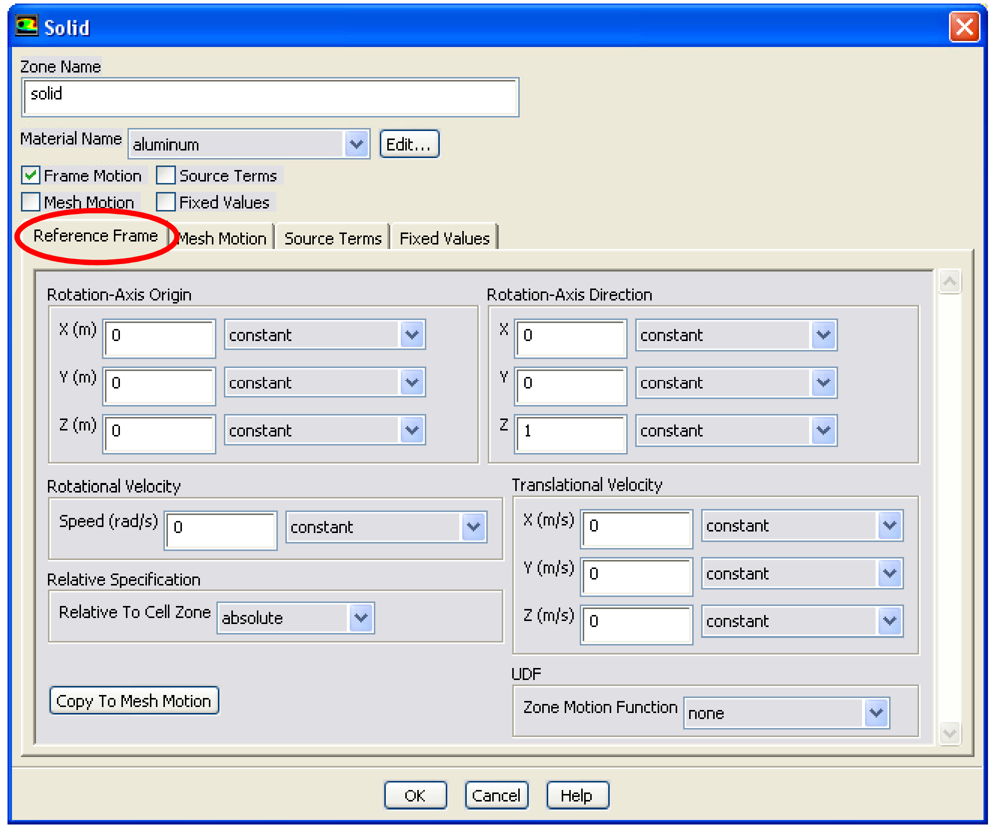
Conduction in Moving Solids

- **The velocity field is taken from the Solid panel (rotation and translation)**
  - **Note that those velocity fields satisfy the continuity equation.**
- **Convection in conducting solids is justified for:**
  - **Solid translation of an extruded geometry (slab, plate or sheet…)**
  - **Solid rotation of a geometry of revolution**



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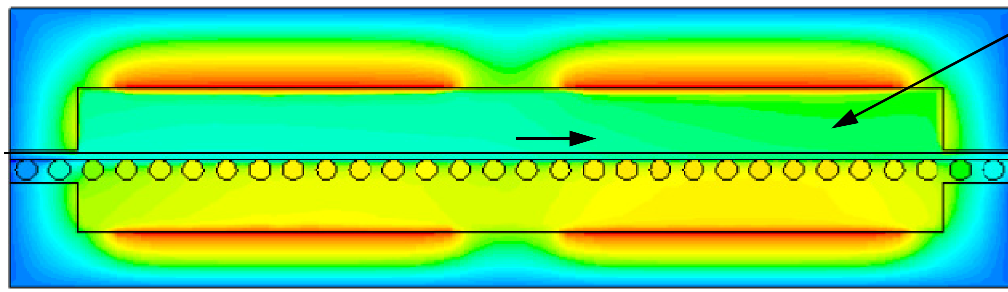
Conduction in Moving Solids

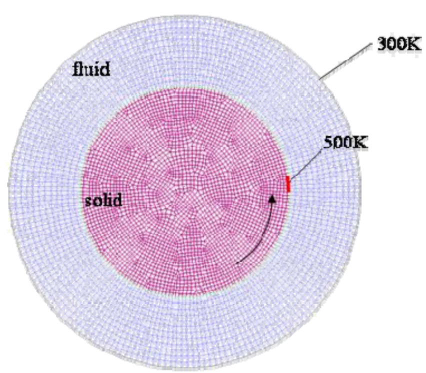
- **Example of convection in conducting solids**
  - **Metal or glass sheet in translation in a furnace.**

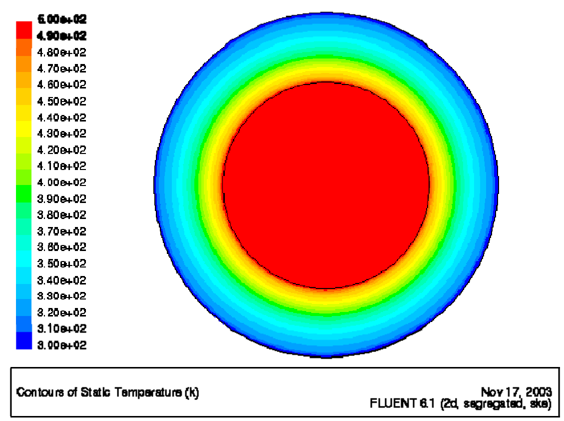


A solid meshed sheet is moving.

Inlet: Prescribed temperature

Outlet: Adiabatic (temperature gradient is 0.)





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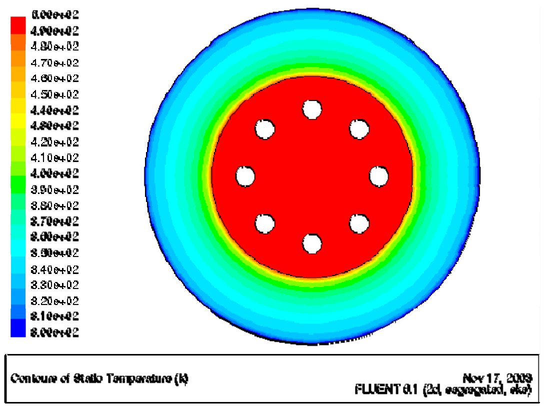
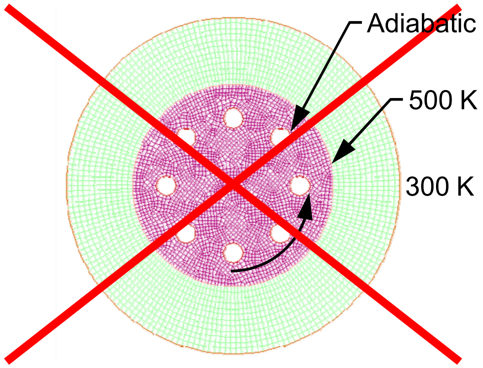
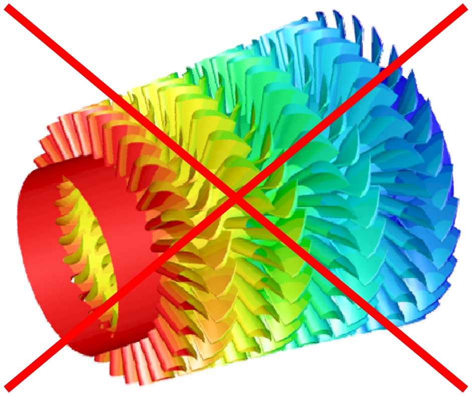
Conduction in Moving Solids

- **Moving reference frame (MRF) is not appropriate for the entire solid zone in the following situations:**
  - **Brake disc with holes**





  - **Turbomachinery blade**



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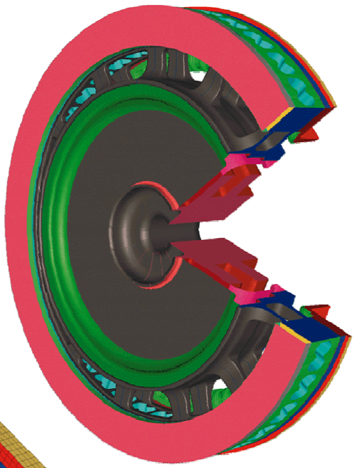
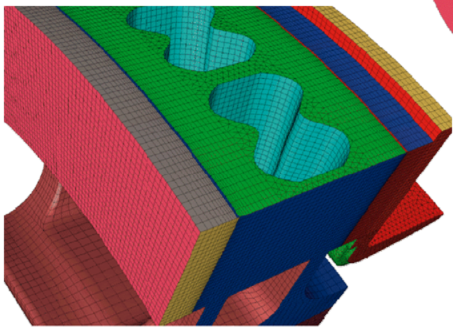
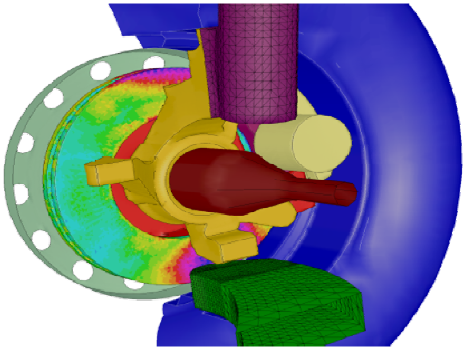
Conduction in Moving Solids

- **Can we treat these problems using a steady approach?**
  - **Just like for the fluid problem the multiple reference frame approach may be a useful approximation.**
  - **Brake disc with holes**
    - **Solid region decomposition**
      - **Solid zone in the MRF (body of revolution)**
      - **Solid zone in the SRF (part with holes). This part may actually be moving. The effect of rotation on heat transfer will be provided by the moving material surrounding this zone.**





Solid Region Decomposition



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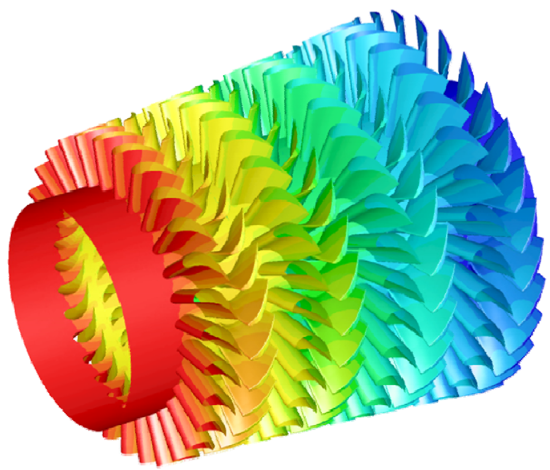
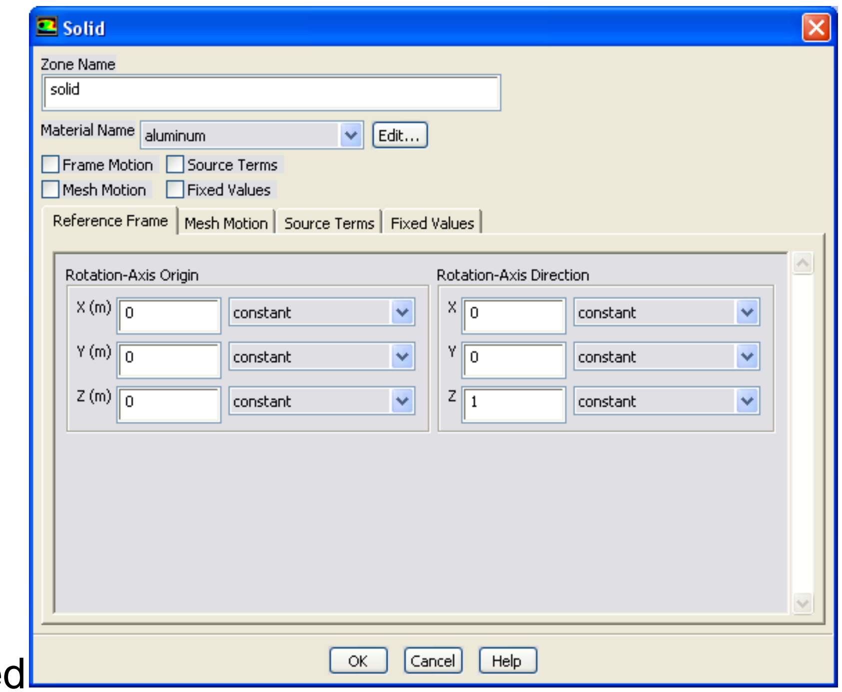
Conduction in Moving Solids

- **Can we treat this problem using a steady approach?**
  - **Turbomachinery blade**





  - Solid zone: Stationary
  - Wall / Shadow: Thermally coupled
  - Wall on solid side: Stationary wall (absolute)
  - Wall/Shadow on fluid side: Moving wall (relative to adjacent cell zone)

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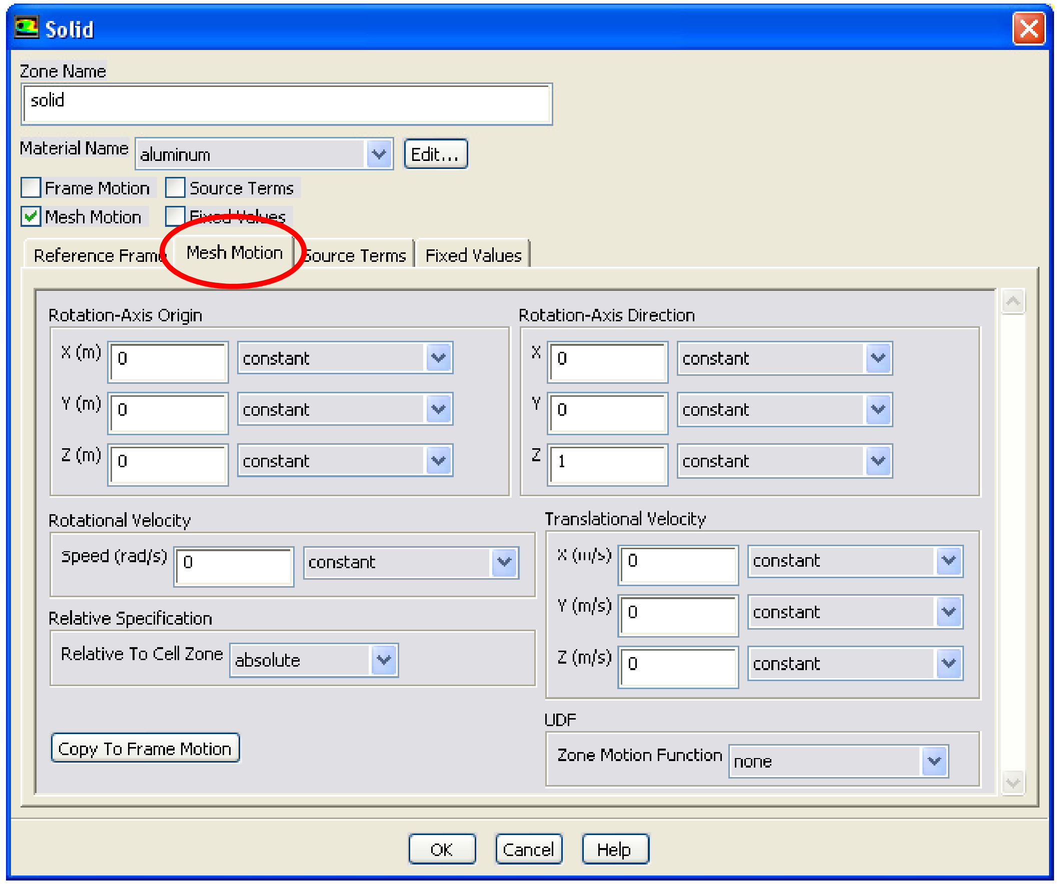
Conduction in Moving Solids

- **Unsteady state?**
  - **Moving reference frame can also be used in unsteady problems with the same limitations as in steady state.**
  - **Sliding mesh or rigid body deforming mesh is a rigorous way of treating the unsteady problem.**
    - **Sliding interface should be located between two fluid zones**



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Conduction in Moving Solids

- **Moving reference frame (MRF) approach is only valid for special cases.**
  - **Rigid-body translation of an extrusion (slab, plate, sheet, …)**
  - **Rigid-body rotation of a solid of revolution**
- **Multiple reference frame**
  - **Moving solid can be treated as stationary if the surrounding fluid or solid is in the same frame of reference**
- **Sliding mesh is often the most accurate approach**

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- Introduction
- Energy equation in solids
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  - Anisotropic conductivity
- Moving solids
- **Solver parameters**

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Solver Parameters

- Convergence difficulties

- Solver parameters affecting solution behavior
  - Single-precision/double-precision solver
  - Explicit relaxation of the energy equation
  - Importance of secondary gradients
  - MultiGrid methods

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Convergence Difficulties

- Convergence difficulties can be recognized by the following symptoms.
  - Overall imbalance in heat flux at boundaries.
  - Slow convergence rate (several thousand iterations)
  - Residuals that diverge
  - Local (cell) temperatures reaching nonphysical values

- Skewed cells and improperly-posed boundary conditions can also cause convergence problems.

- These problems can be either mitigated or avoided completely through simple modifications to the solution setup.

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Double-Precision Solver

- **The double-precision solver is designed to minimize truncation error and thus improve the overall heat balance.**

`fluent 2ddp` **or** `fluent 3ddp`

- **As a general rule, the double precision solver should be enabled under the following conditions:**
  - **Cases with large heat fluxes (order of MW)**
    - **Large, possibly solution-dependent heat sources in the energy equation.**
    - **Widely varying fluid properties (functions of temperature) such as nonlinear solids or compressible gases/liquids.**
  - **Cases where there are large differences in thermal conductivity among materials.**
    - **Energy equation numerics become stiff.**
    - **Flux matching conditions become more difficult to maintain at solid interfaces.**

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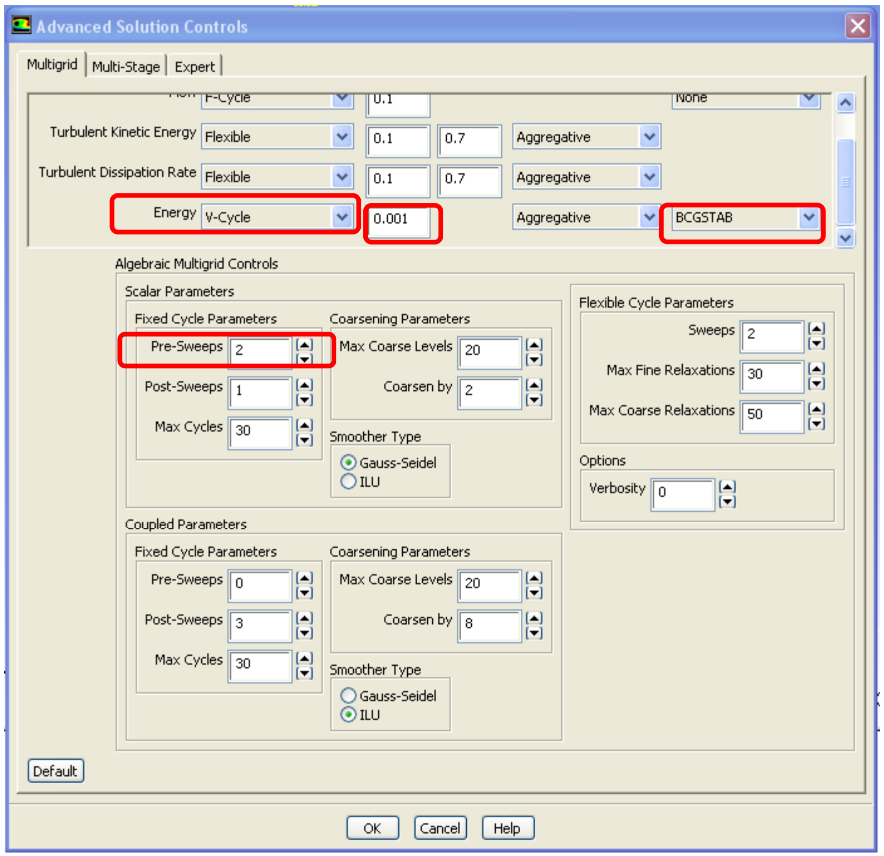
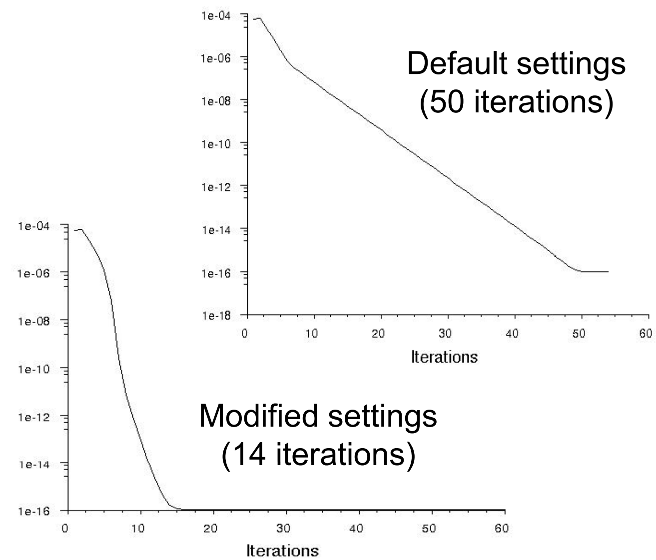
MultiGrid Solver Parameters

- **MultiGrid Methods**
  - **The default MultiGrid scheme on energy equation is Flexible**
  - **Using either the W-Cycle or F-Cycle scheme is preferred when diffusion is the predominant effect**
    - **W-Cycle is recommended for serial processing**
    - **V-Cycle or F-Cycle is recommended for parallel processing**





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Explicit Under-Relaxation

- **Scheme command to activate explicit under-relaxation of temperature (enter as you would any TUI command).**

```
(rpsetvar ‘temperature/explicit-relax? #t)
```

- **Advantages**
  - **Improved convergence for poor quality meshes**
  - **Improved convergence when material properties are strongly dependent on temperature**
- **Motivation**
  - **Energy under-relaxation factor of 1 often recommended**
  - **Temperature under-relaxation may be preferred**
- **Settings:**
  - **Once the Scheme command is activated, the energy under-relaxation is regarded as a temperature under-relaxation**
  - **Temperature URF typically 0.2–0.5 and energy URF = 1**

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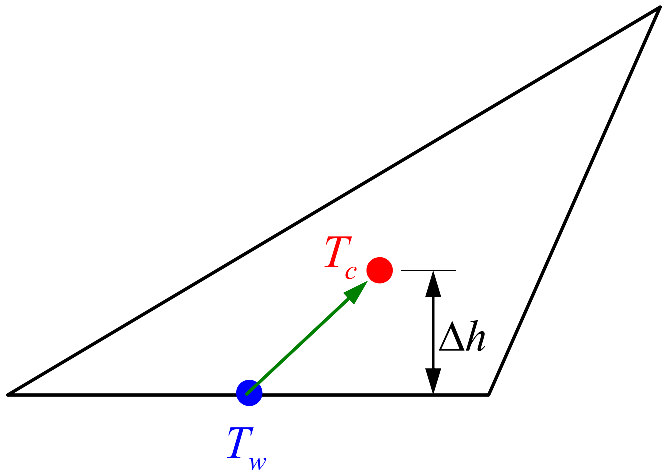
Secondary Gradients

- **What is a secondary gradient?**
  - **Secondary gradients are used primarily as a corrective measure (the flux vector may not be parallel to the face normal vector)**



$$q = k\,\nabla T \cdot \mathbf{n}$$
$$= k\,\frac{T_w - T_c}{\Delta h} + f(\Delta T)$$

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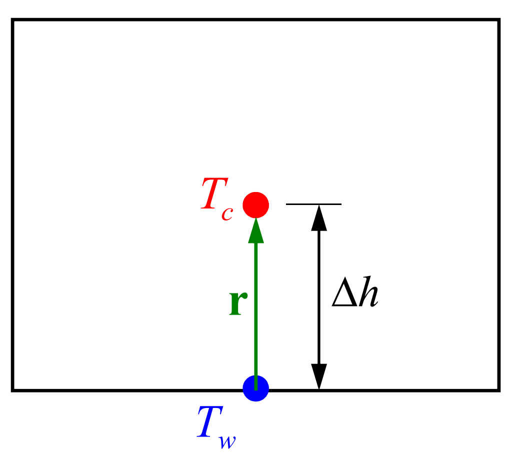
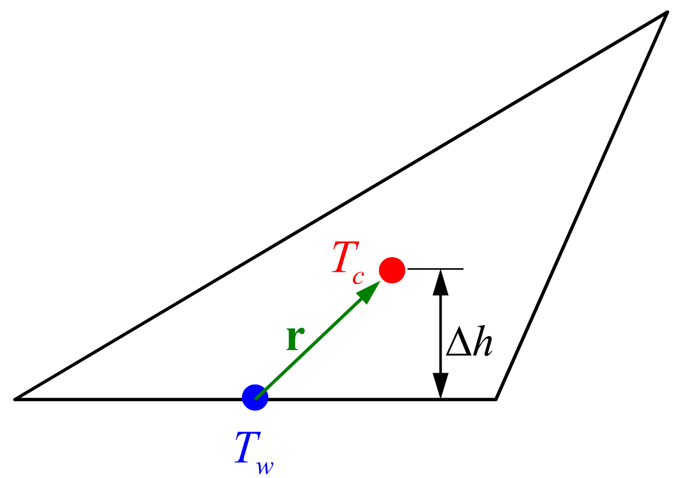
Secondary Gradients

- **Influence of secondary gradients**
  - **The secondary gradient effect increases with mesh skewness. With poor mesh (skewness greater than 0.9), disabling secondary gradient treatment will aid in convergence.**



Perfect Hexahedral Mesh
Secondary Gradient = 0



Skewed Tetrahedral Mesh
Secondary Gradient depends on skewness

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Secondary Gradients

- **Secondary gradient influence**
  - **With poor mesh (skewness greater than 0.9), disabling secondary gradient treatment will aid in convergence.**
  - **3 possibilities :**
    - **Disable secondary gradients in all zones**

      ```
      (rpsetvar 'temperature/secondary-gradient? #f)
      ```

    - **Disable secondary gradients only on wall zones**

      ```
      solve/set/expert/
         use-alternate-formulation-for-wall-temperature? yes
      ```

    - **Disable secondary gradients only on shell conduction zones**

      ```
      (rpsetvar 'temperature/shell-secondary-gradient? #f)
      ```

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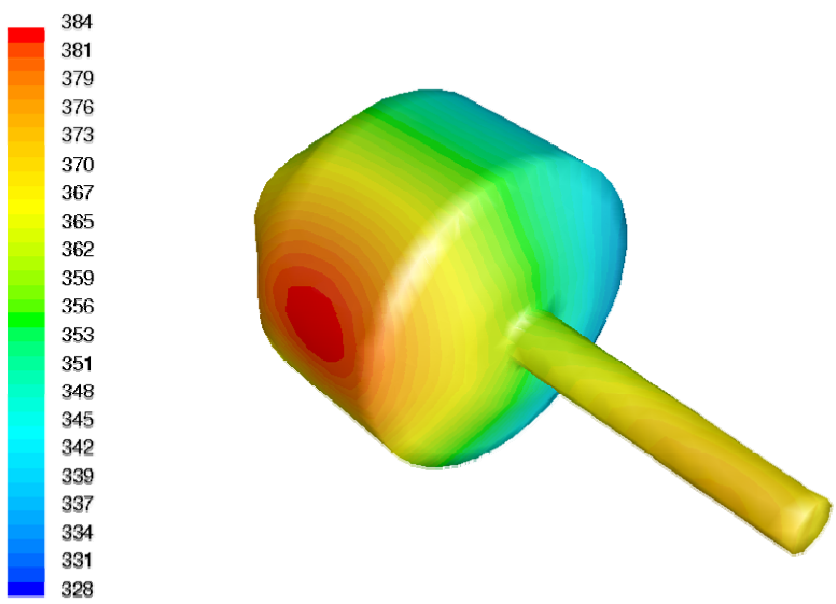
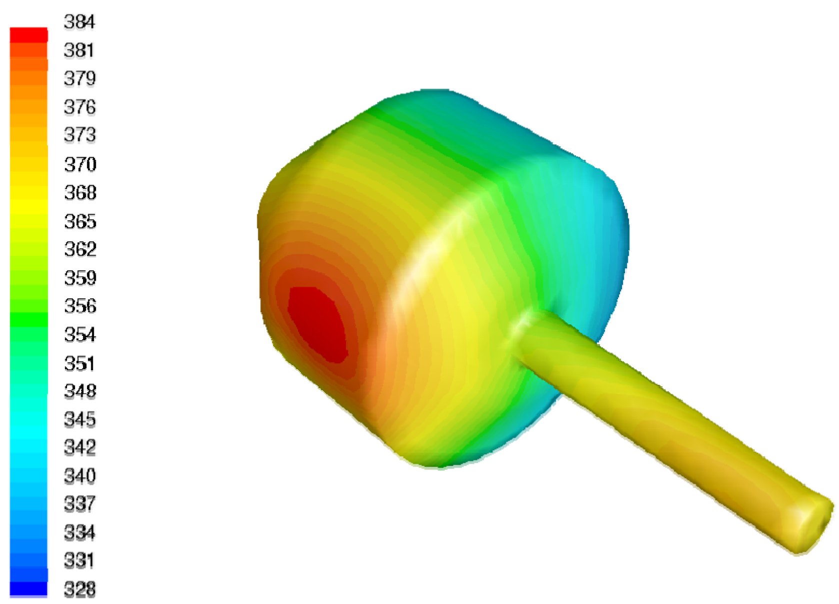
Secondary Gradients

- **Is accuracy compromised by neglecting secondary gradients?**

Default



Without Secondary Gradients



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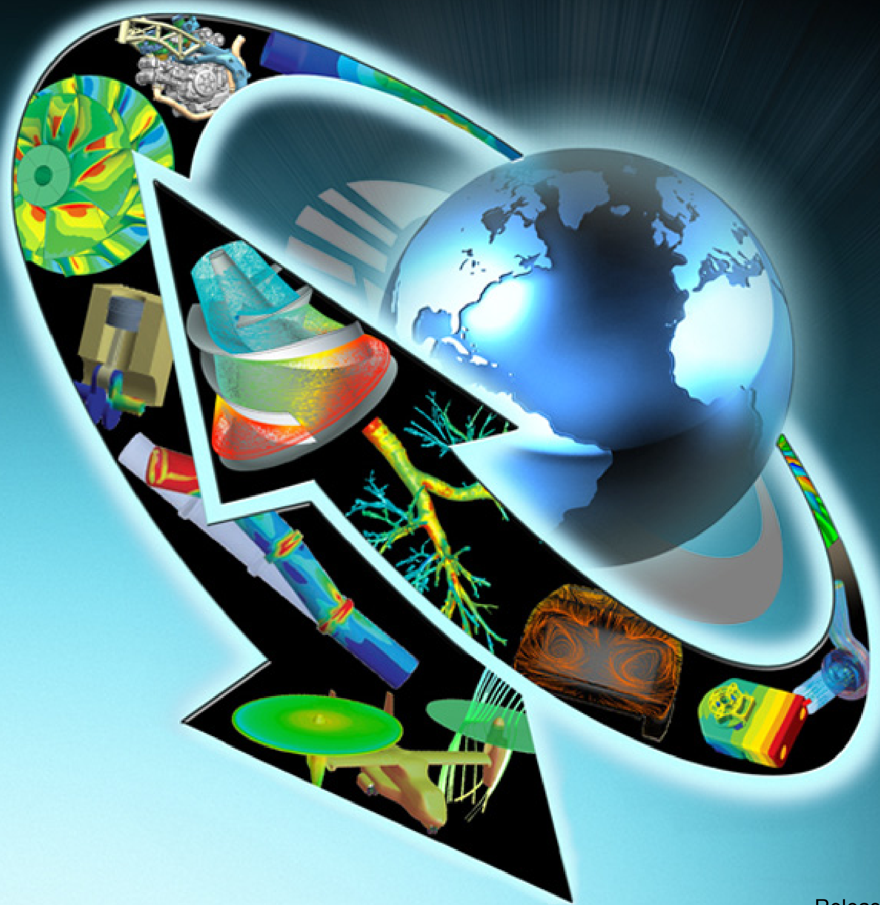
Appendix

Lecture 2

Conduction Heat Transfer



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Thermal Conductivity of Selected Materials

Material	Thermal Conductivity at 20 °C (W/m·K)
Silver	430
Copper	387
Aluminum	202
Steel	16
Glass	1
Water	0.6
Wood	0.17
Glass wool	0.04
Polystyrene	0.03
Air	0.024

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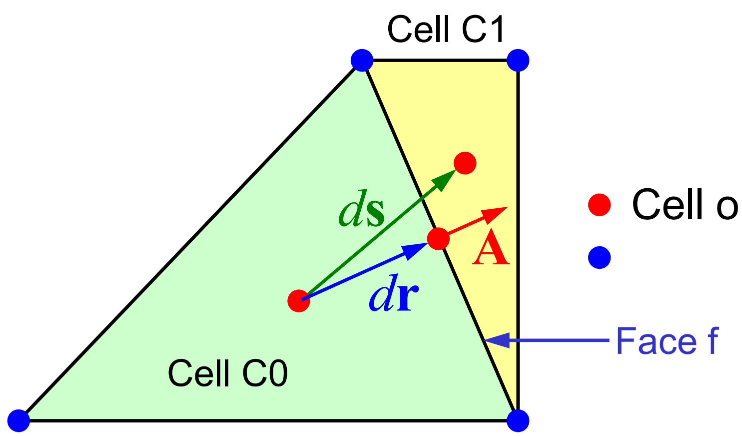
Conductive Flux Calculation

- **Diffusive flux on an interior face**
  - **φ = Temperature for conduction**
  - **k = Thermal conductivity**

$$\mathbf{e}_s = \frac{d\mathbf{s}}{\|d\mathbf{s}\|}$$

$$D_f = k_f \, \nabla\phi \cdot \mathbf{A}$$

$$\approx \underbrace{k_f \frac{\phi_1 - \phi_0}{ds} \frac{\mathbf{A}\cdot\mathbf{A}}{\mathbf{A}\cdot\mathbf{e}_s}}_{\text{Primary flux}} + \underbrace{k_f \left(\nabla\phi \cdot \mathbf{A} - \nabla\phi \cdot \mathbf{e}_s \frac{\mathbf{A}\cdot\mathbf{A}}{\mathbf{A}\cdot\mathbf{e}_s} \right)}_{\text{Secondary gradient}}$$



● Cell or face centroid
● Node

The flux at a boundary face has a similar expression, ϕ_1 is replaced by ϕ_f and d**s** replaced by d**r**

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