Heat Transfer Modeling

Introductory FLUENT Training

Outline

- Energy Equation
- Wall Boundary Conditions
- Conjugate Heat Transfer
- Thin and two-sided walls
- Natural Convection
- Radiation Models
- Reporting - Export

Energy Equation – Introduction

- Energy transport equation:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot \left[\vec{V}(\rho E + p)\right] = \nabla \cdot \left[\underbrace{k_{\text{eff}} \nabla T}_{\text{Conduction}} - \underbrace{\sum_j h_j J_j}_{\text{Species Diffusion}} + \underbrace{\left(\overline{\overline{\tau}}_{\text{eff}} \cdot \vec{V}\right)}_{\text{Viscous Dissipation}} \right] + S_h$$

  - Energy E per unit mass is defined as:

$$E = h - \frac{p}{\rho} + \frac{V^2}{2}$$

  - Pressure work and kinetic energy are always accounted for with compressible flows or when using the density-based solvers. For the pressure-based solver, they are omitted and can be added through the text command:

```
Define/models/energy?
```

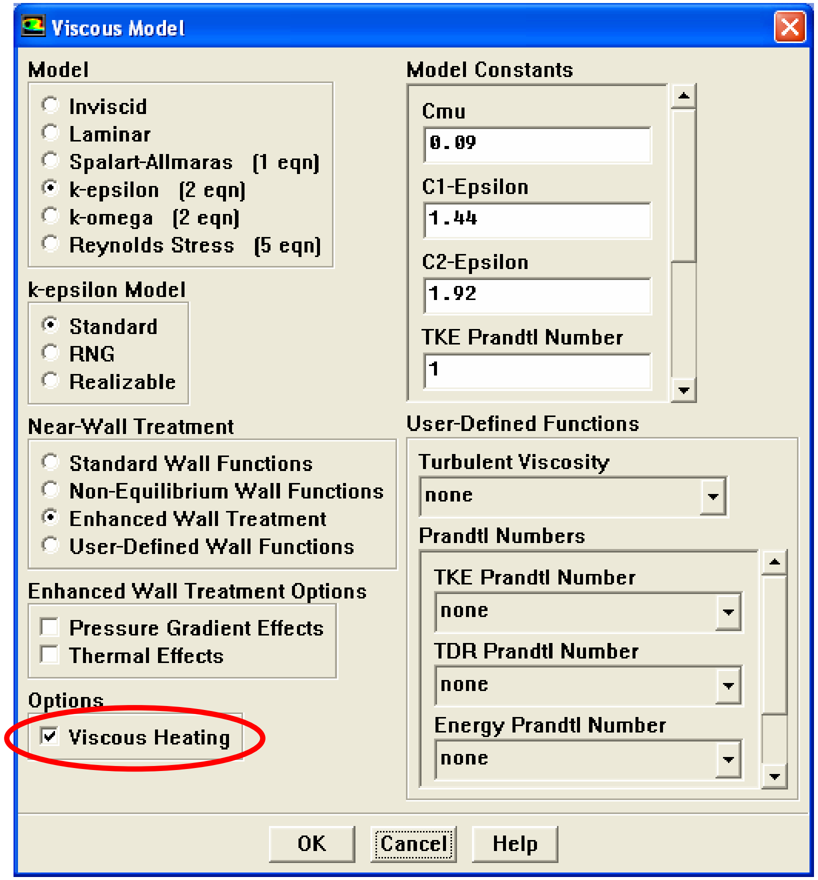
Energy Equation Terms – Viscous Dissipation

- Energy source due to viscous dissipation:

$$\nabla \cdot \left(\overline{\overline{\tau}}_{\text{eff}} \cdot \vec{V} \right)$$

  - Also called viscous heating.
  - Important when viscous shear in fluid is large (e.g. lubrication) and/or in high-velocity compressible flows.
  - Often negligible
    - Not included by default in the pressure-based solver.
    - Always included in the density-based solver.
  - Important when the Brinkman number approaches or exceeds unity:

$$\text{Br} = \frac{\mu U_e^2}{k\,\Delta T}$$

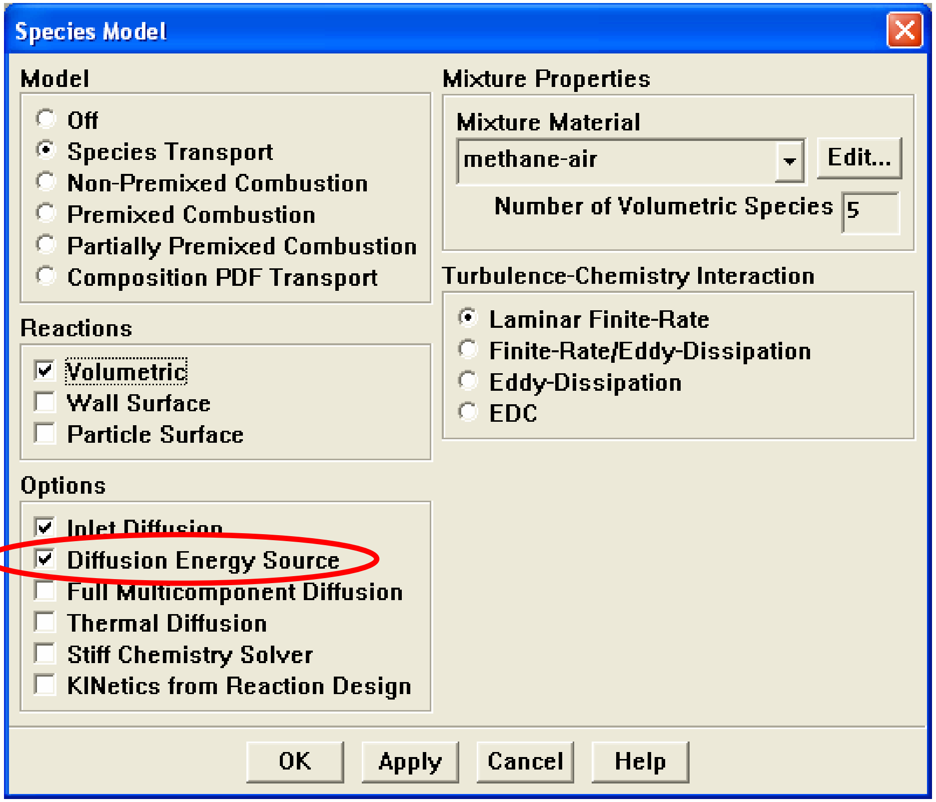


Energy Equation Terms – Species Diffusion

- Energy source due to species diffusion included for multiple species flows.

$$\nabla \cdot \left(\sum_j h_j J_j \right)$$

  - Includes the effect of enthalpy transport due to species diffusion
  - Always included in the density-based solver.
  - Can be disabled in the pressure-based solver.



Energy Equation Terms (3)

- Energy source due to chemical reaction is included for reacting flows.
  - Enthalpy of formation of all species.
  - Volumetric rate of creation of all species.
- Energy source due to radiation includes radiation source terms.
- Interphase energy source:
  - Includes heat transfer between continuous and discrete phase
  - DPM, spray, particles…

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot \left[\vec{V}(\rho E + p)\right] = \nabla \cdot \left[k_{\text{eff}} \nabla T - \sum_j h_j J_j + \left(\bar{\bar{\tau}}_{\text{eff}} \cdot \vec{V}\right)\right] + \boxed{S_h}$$

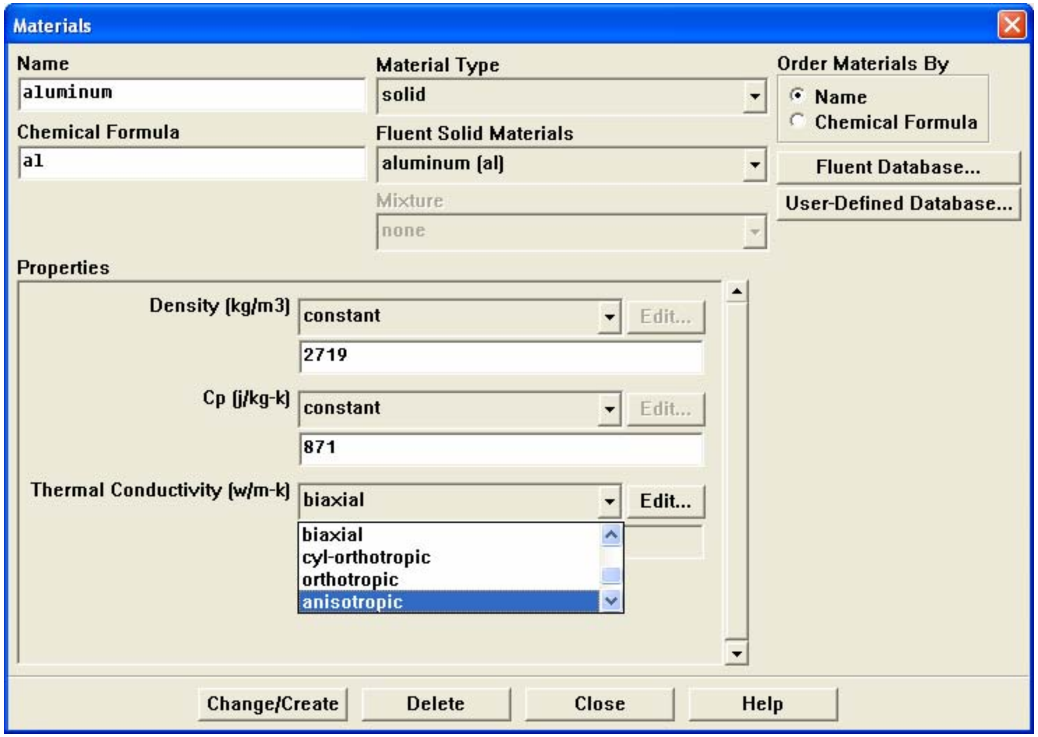
Energy Equation for Solid Regions

- Ability to compute conduction of heat through solids
- Energy equation: $$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot \left(\vec{V} \rho h\right) = \nabla \cdot (k \nabla T) + S_h$$
  - H is the sensible enthalpy:

$$h = \int_{T_{\text{ref}}}^{T} c_p \, dT$$

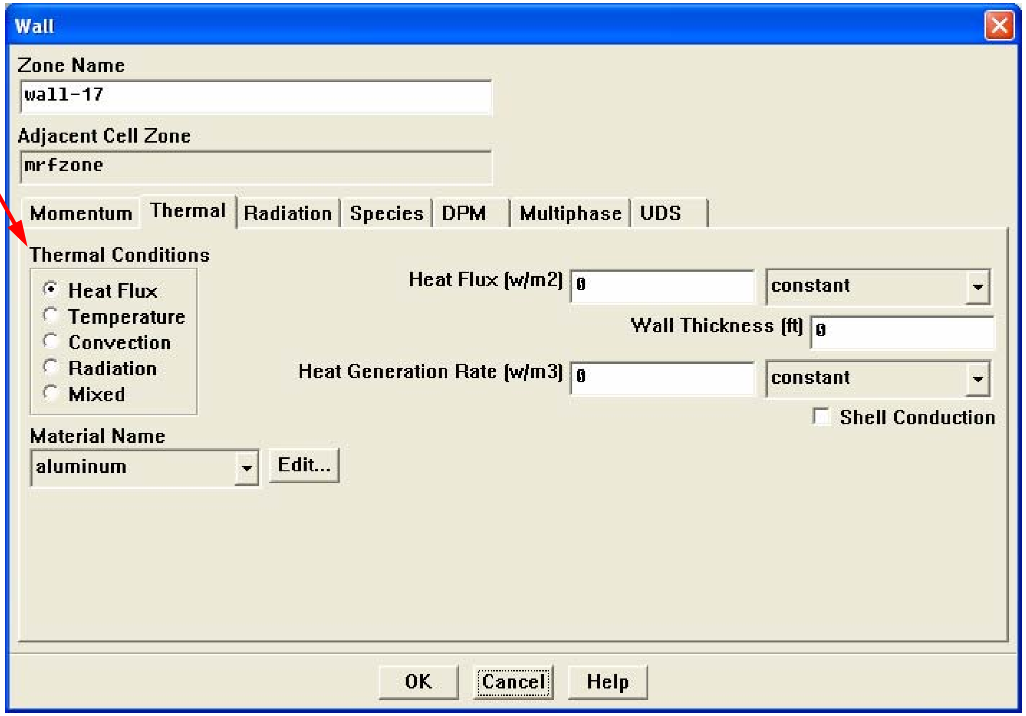
- Anisotropic conductivity in solids (pressure-based solver only)

$$\nabla \cdot (k_{ij} \nabla T)$$



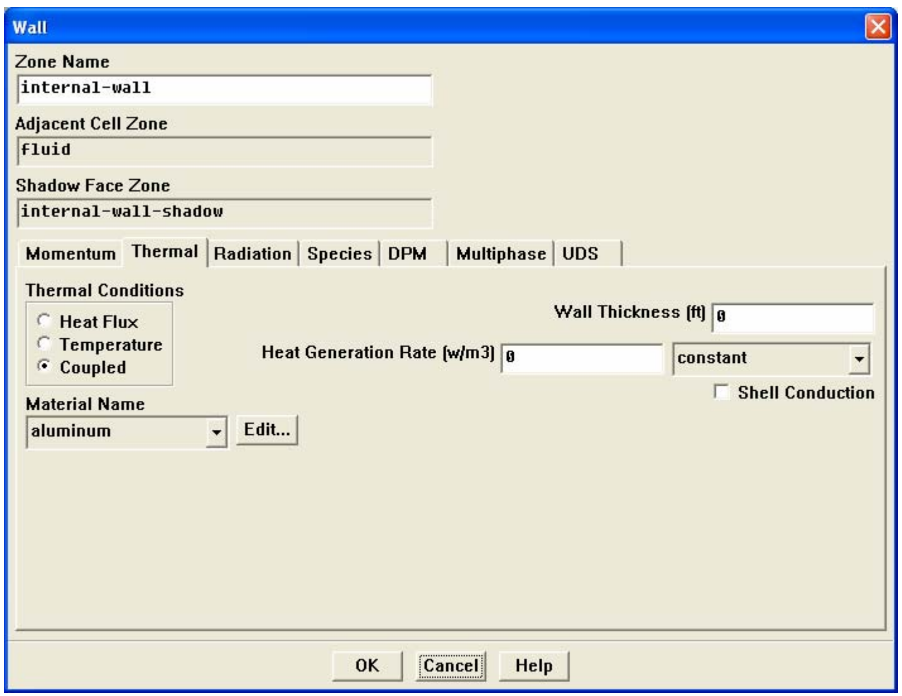
Wall Boundary Conditions

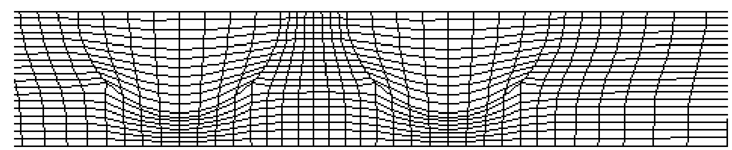
- Five thermal conditions
- Radiation
  - Heat transfer from exterior of model
  - Requires external emissivity and external radiation temperature.
- Mixed
  - Combined Convection and External
    Radiation Boundary Conditions
- Wall material and thickness can be defined for 1D or shell conduction calculations.
  heat transfer calculations.



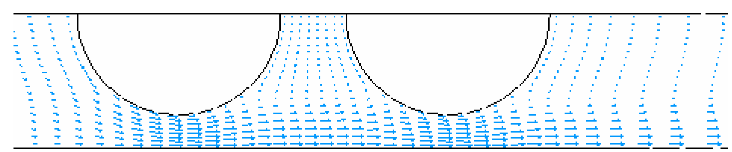
Conjugate Heat Transfer

- Ability to compute conduction of heat through solids, coupled with convective heat transfer in fluid.
- The Coupled boundary condition is available to any wall zone which separates two cell zones.

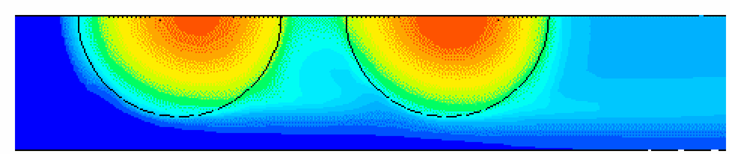




Grid



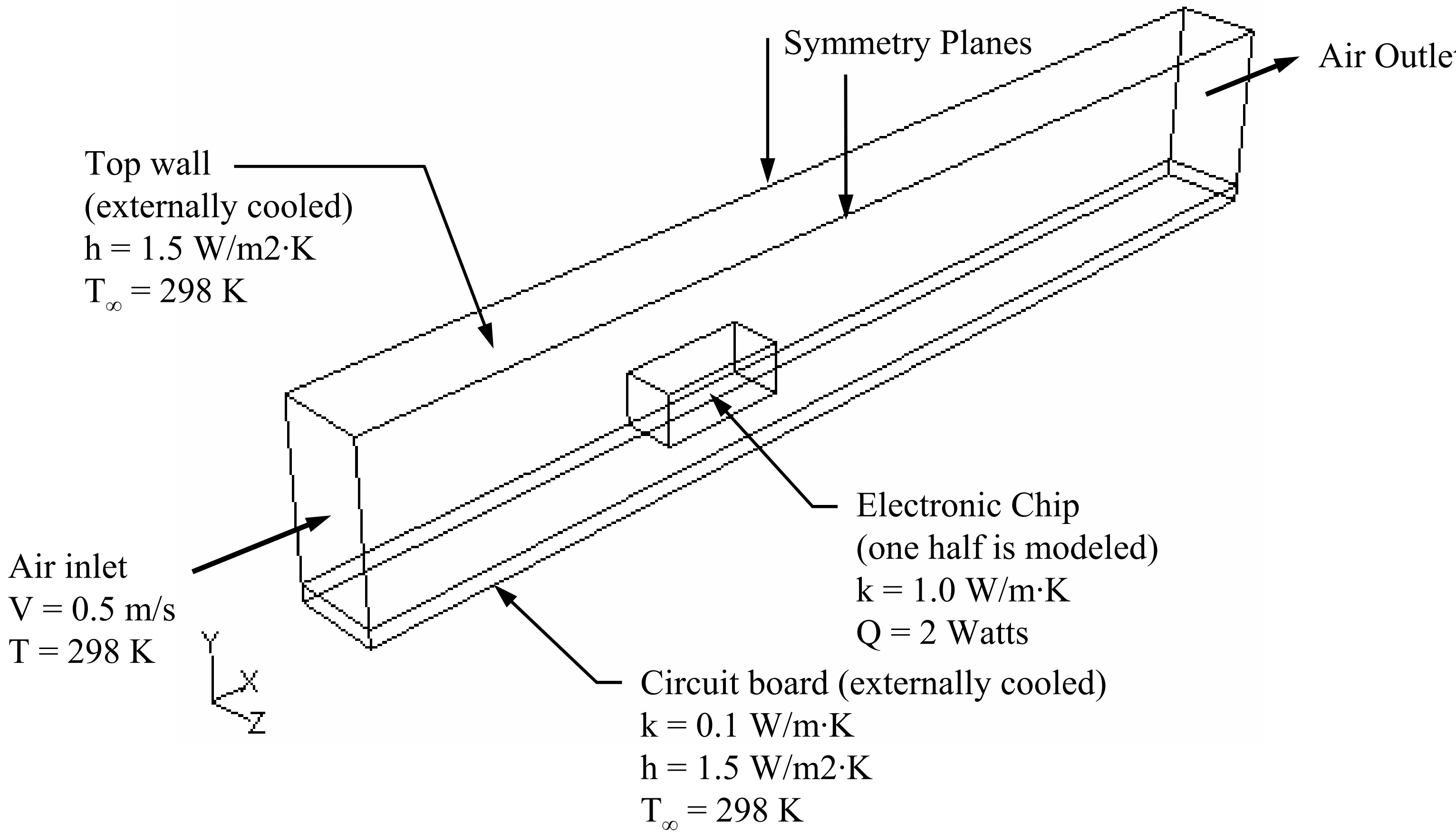
Velocity vectors



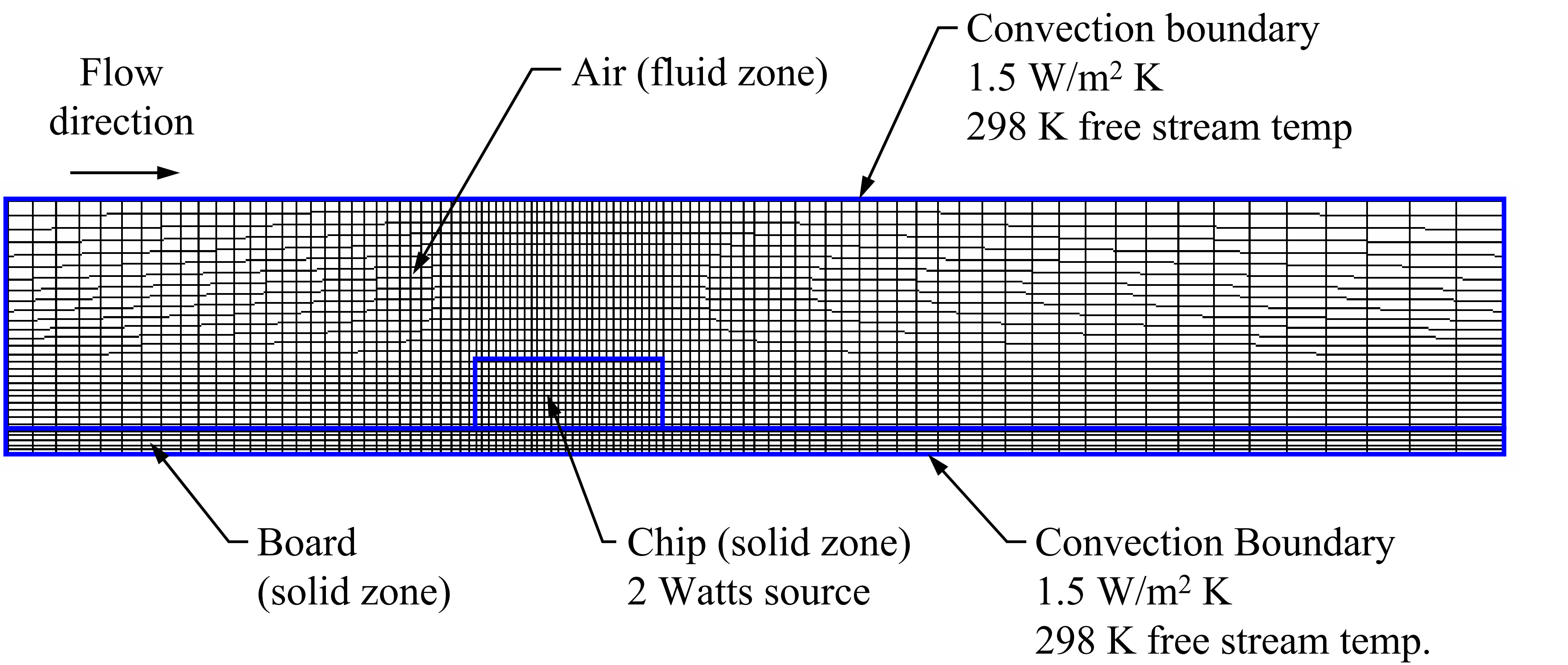
Temperature contours

Example -- Cooling Flow over Fuel Rods

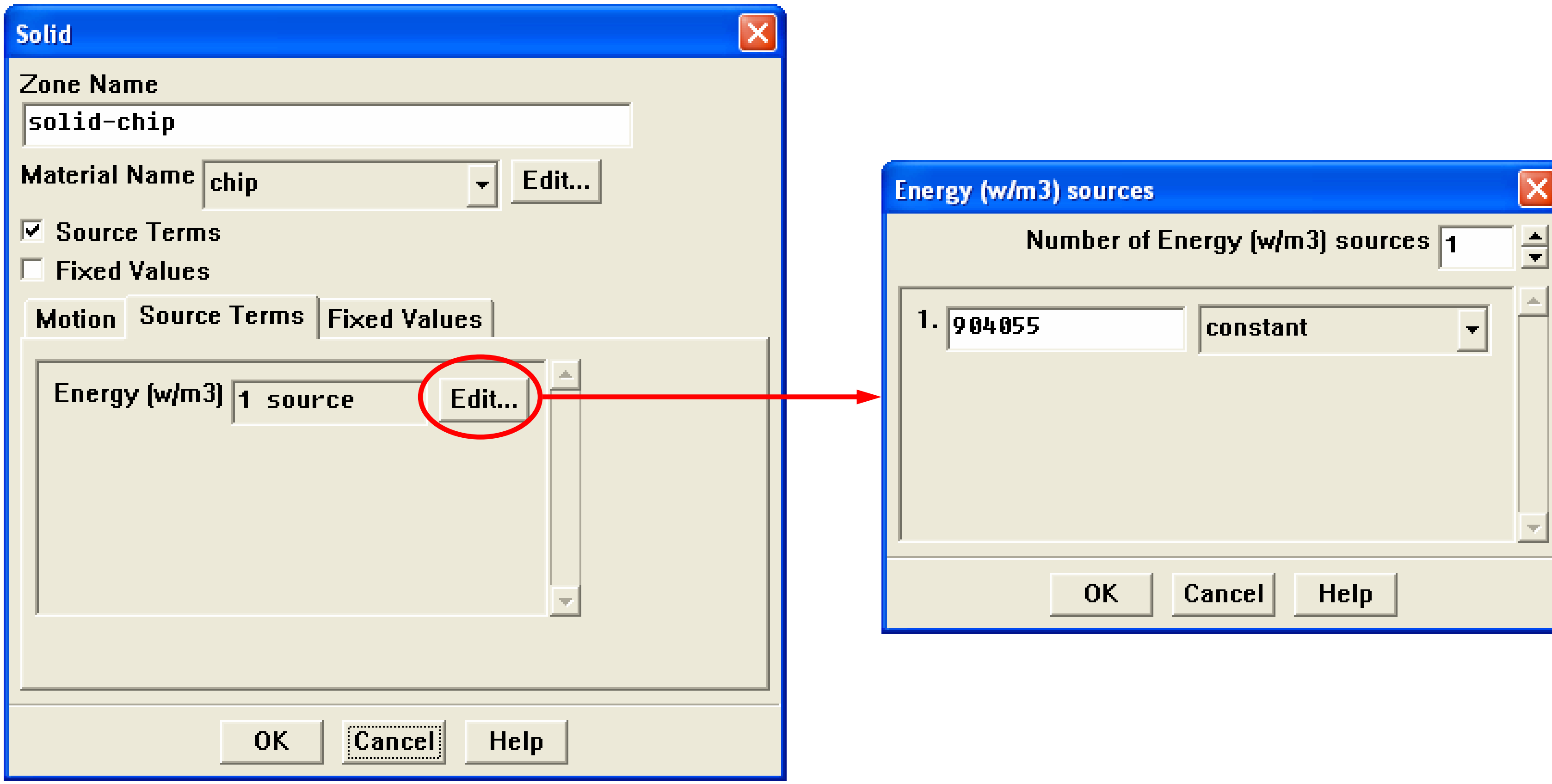
Conjugate Heat Transfer Example



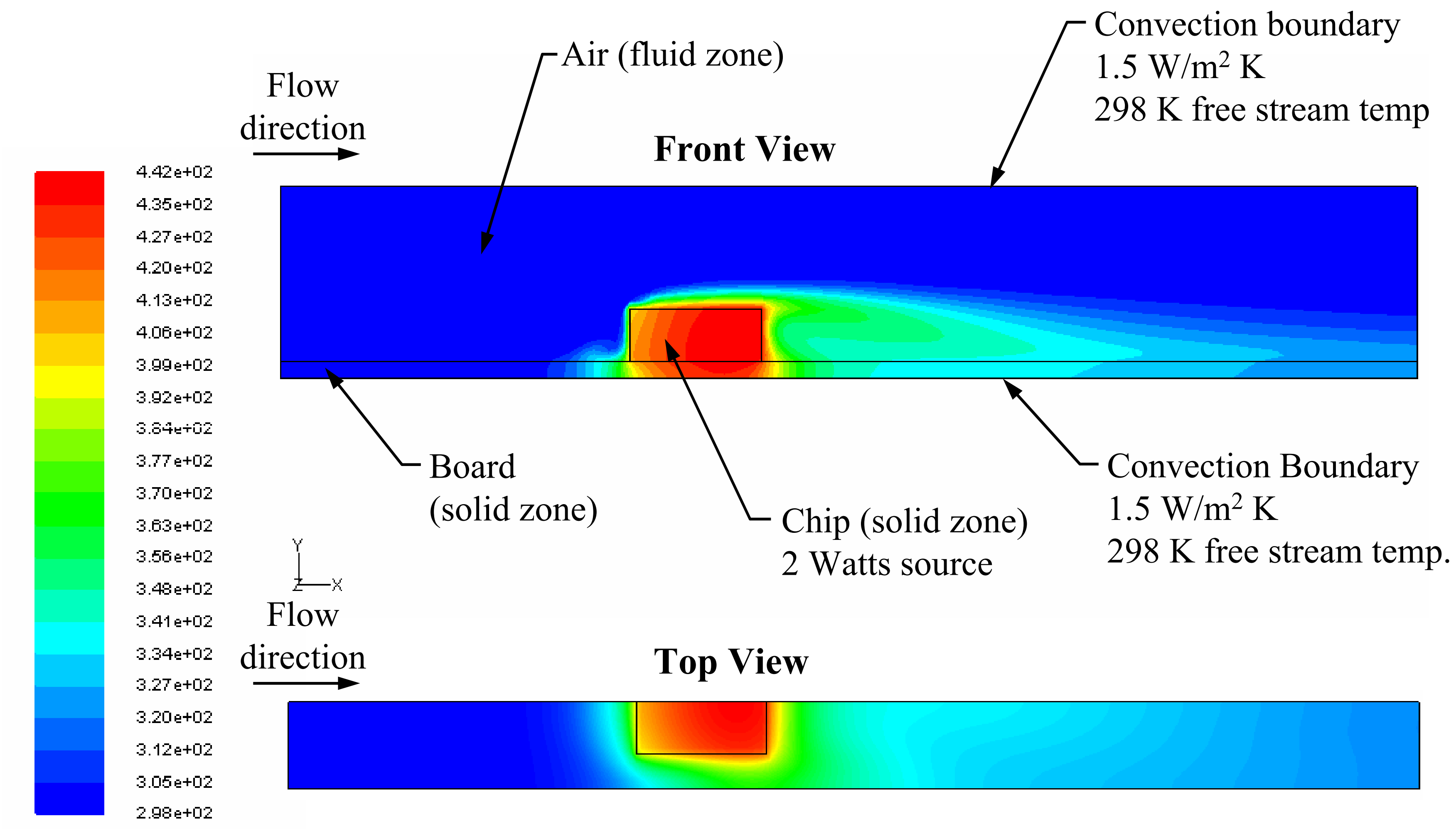
Example – 3D Mesh and BC's



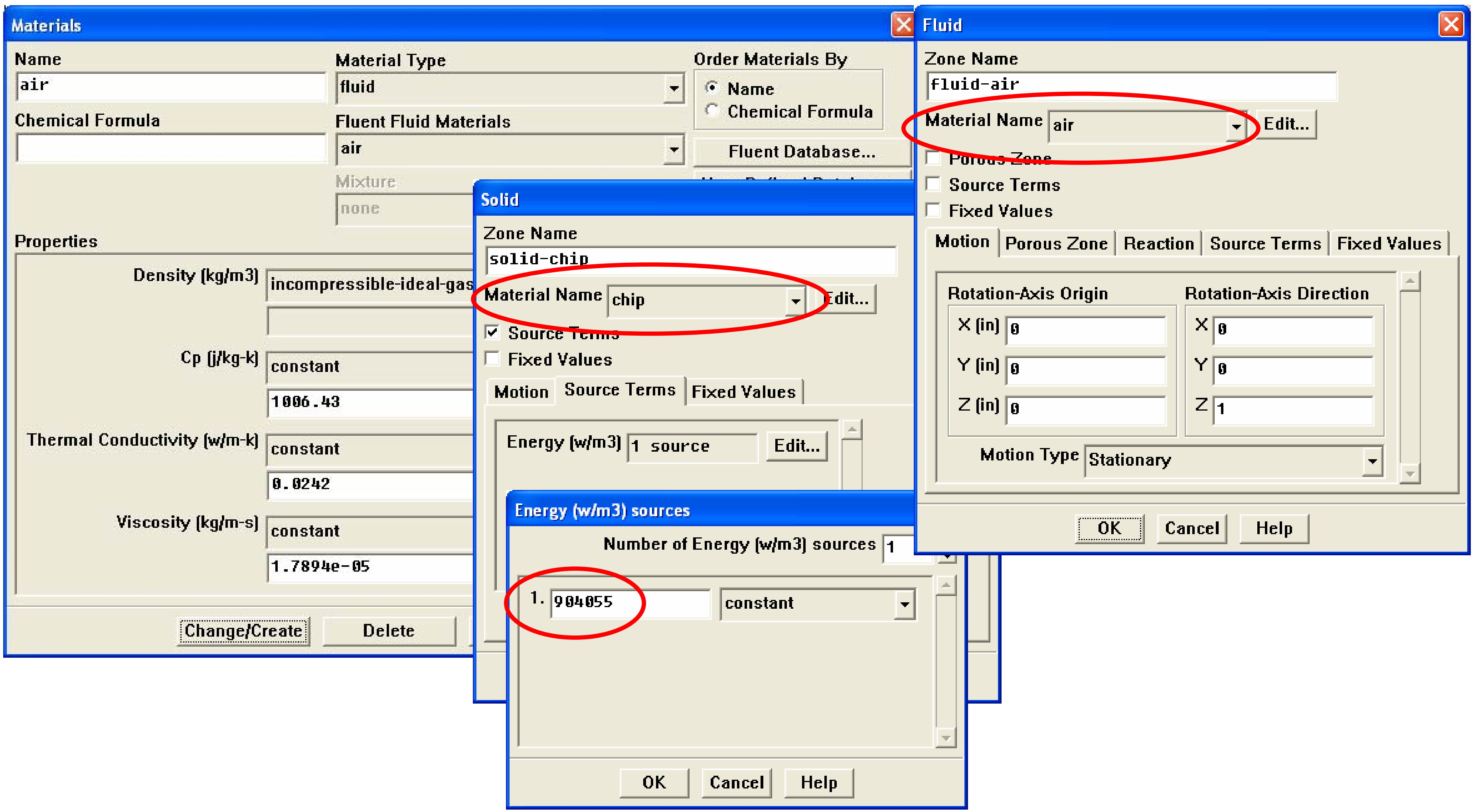
Problem Setup – Heat Source



Temperature Distribution (Front and Top View)

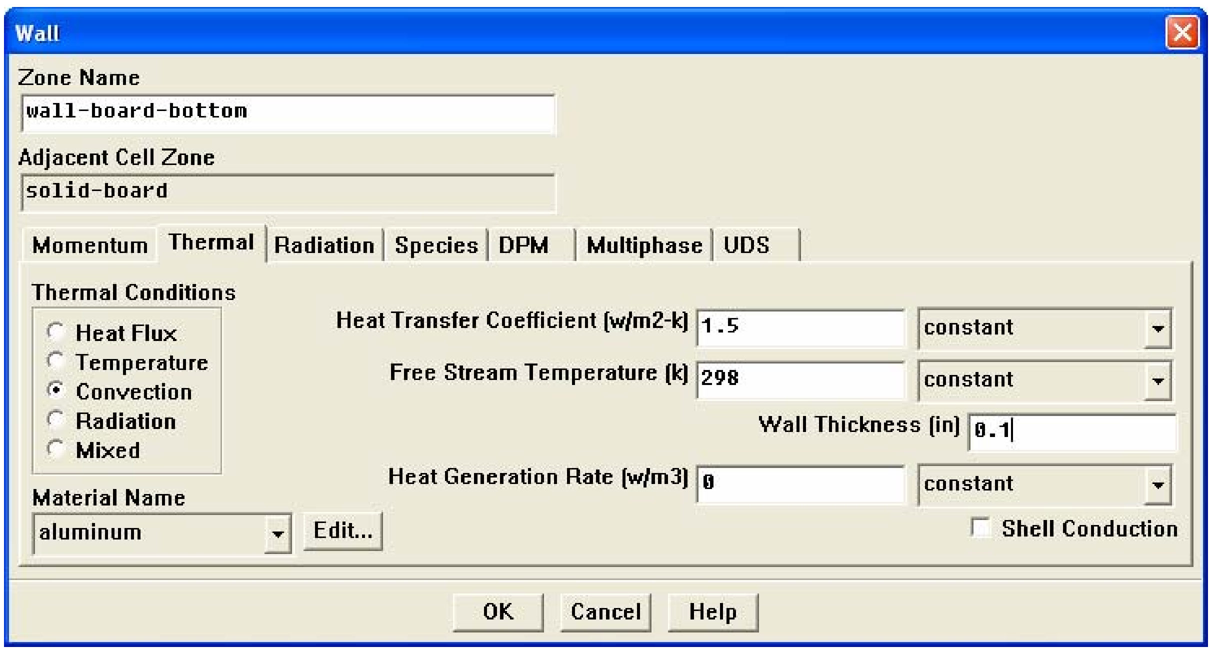


Conjugate Heat Transfer Setup



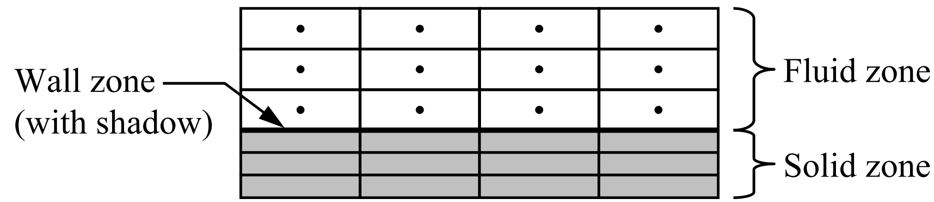
Alternate Modeling Strategies

- An alternate treatment of the board surface would be to model it as a wall with specified thickness (Thin Wall model).
- In this case, there would be no need to mesh the lower solid zone (representing the board).



Two Approaches for Wall Heat Transfer

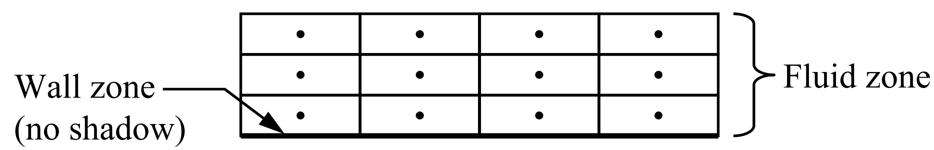
- Meshed wall
  - Energy equation is solved in a solid zone representing the wall.
  - Wall thickness must be meshed.
  - This is the most accurate approach but requires more meshing effort.
  - Always uses the coupled thermal boundary condition since there are cells on both sides of the wall.



Wall thermal resistance directly accounted for in the Energy equation; Through-thickness temperature distribution is calculated.

Bidirectional heat conduction is calculated.

- Thin wall
  - Artificially models the thickness of the wall (specified on the wall BC panel).
  - Uses the coupled thermal boundary condition only for internal walls.

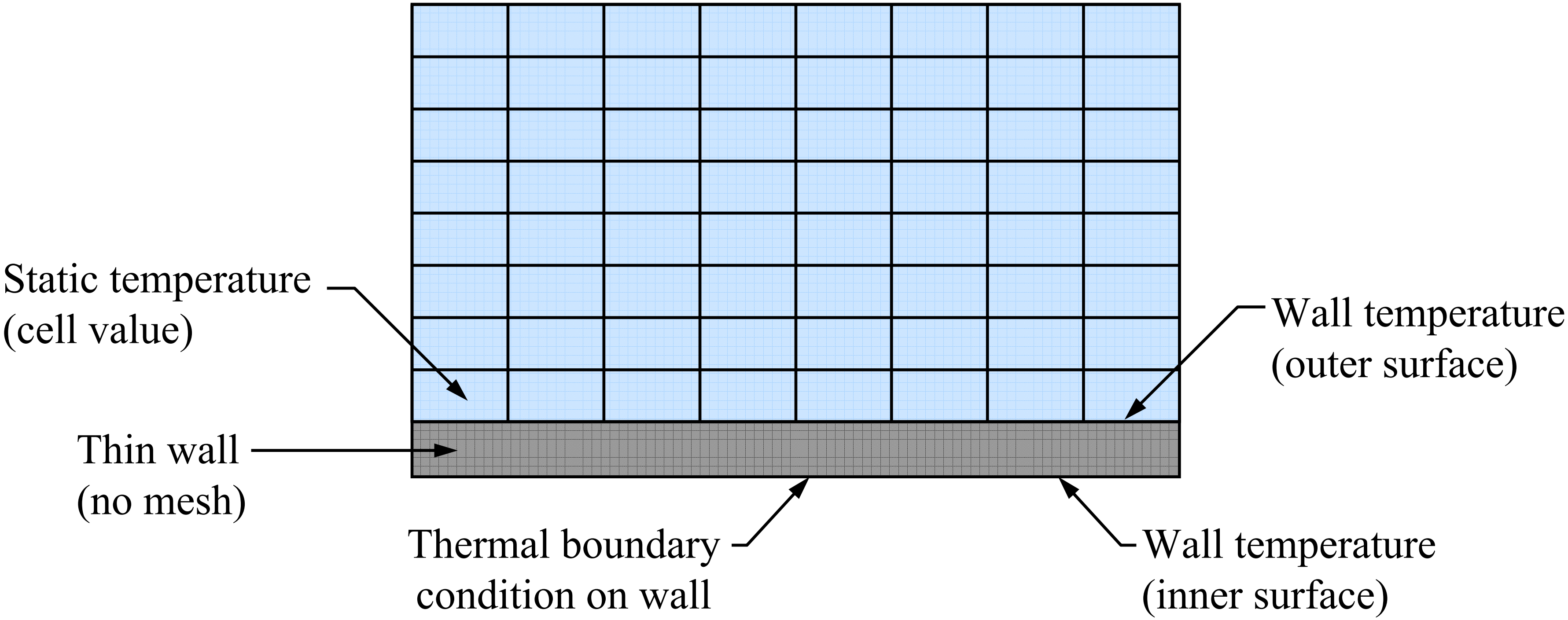


Wall thermal resistance calculated using artificial wall thickness and material type. Through-thickness temperature distribution is assumed to be linear.

Conduction only calculated in the wall-normal direction.

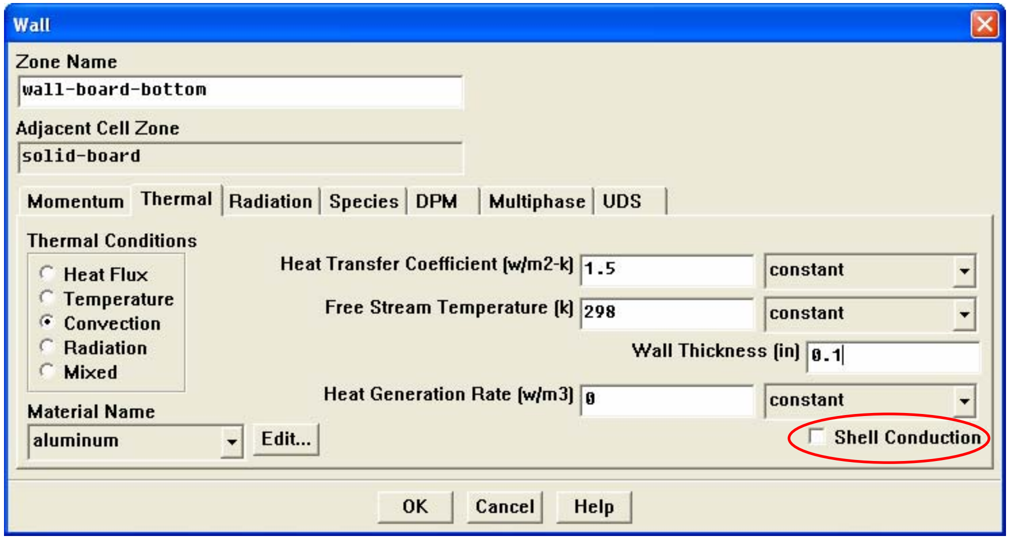
Temperature Definitions for Thin Wall Model

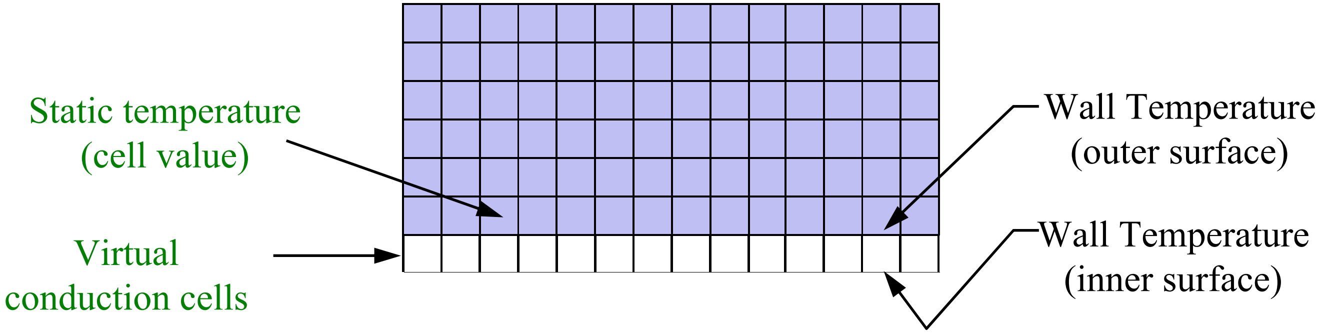
- Thin wall model applies normal conduction only (no in-plane conduction) and no actual cells are created.
- Wall thermal boundary condition is applied at the outer layer



Shell Conduction Option for Wall Heat Transfer

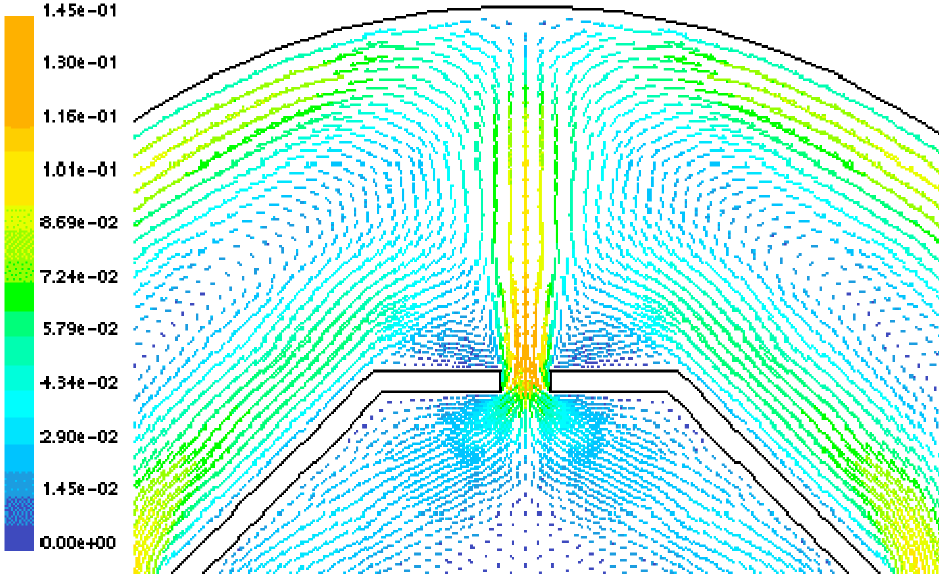
- The shell conduction option is used to enable in-plane conduction calculations.
- Additional conduction cells are created but can not be displayed and cannot be accessed by UDFs.
- Solid properties of the conduction zones must be constant and can not be specified as temperature-dependent.





Natural Convection – Introduction

- Natural convection occurs when heat is added to fluid and fluid density varies with temperature.
- Flow is induced by force of gravity acting on density variation.
- When gravity term is included, pressure gradient and body force term in the momentum equation are re-written as:



$$-\frac{\partial p}{\partial x} + \rho g \Rightarrow -\frac{\partial p'}{\partial x} + (\rho - \rho_0) g$$

where $p' = p - \rho_0\, g\, x$

- This format avoids potential roundoff error when gravitational body force term is included.

Natural Convection – the Boussinesq Model

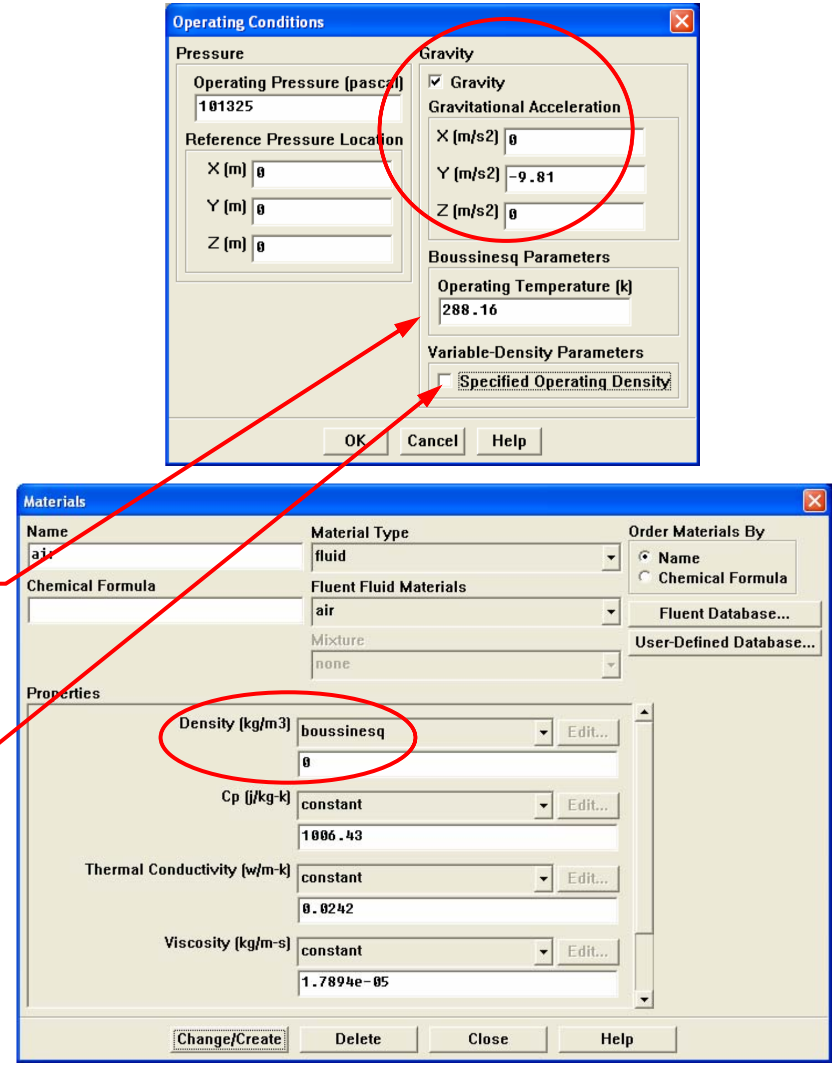
- Boussinesq model assumes the fluid density is uniform except for the body force term in the momentum equation along the direction of gravity, we have:

  $$(\rho - \rho_0) g = -\rho_0 \beta (T - T_0) g$$

  - Valid when density variations are small (i.e., small variations in T).
- It provides faster convergence for many natural-convection flows than by using fluid density as function of temperature.
  - Constant density assumptions reduces non-linearity.
  - Suitable when density variations are small.
  - Cannot be used together with species transport or reacting flows.
- Natural convection problems inside closed domains:
  - For steady-state solver, Boussinesq model must be used.
    - The constant density, ρ_0, properly specifies the mass of the domain.
  - For unsteady solver, Boussinesq model or ideal gas law can be used.
    - Initial conditions define mass in the domain.

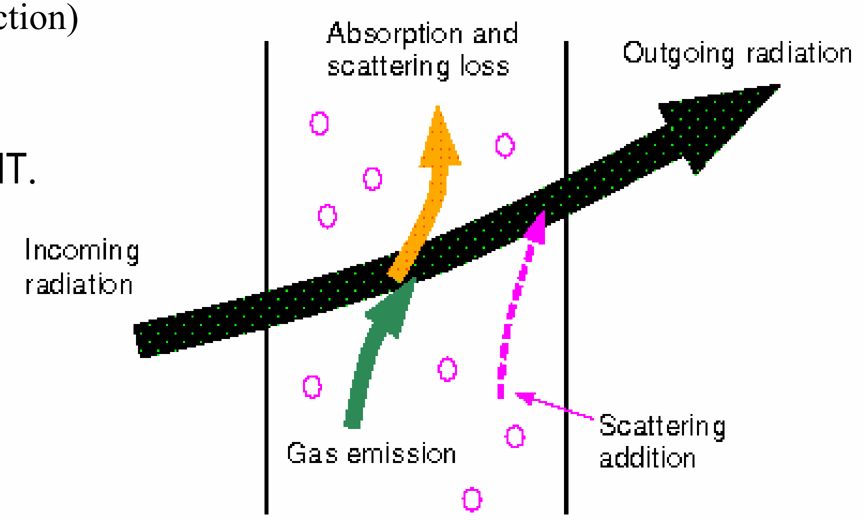
User Inputs for Natural Convection

- Define the gravitational acceleration.
  $\boxed{\text{Define}}$ → Operating Conditions...
- Define density model.
  - If using Boussinesq model:
    - Select boussinesq as the Density method and assign constant value, ρ_0.
      $\boxed{\text{Define}}$ → Materials...
    - Set Thermal Expansion Coefficient, β.
    - Set Operating Temperature, T_0.
  - If using a temperature-dependent model, (e.g., ideal gas or polynomial):
    - Specify Operating Density or,
    - Allow FLUENT to calculate ρ_0 from a cell average (default, every iteration).



Radiation

- Radiation effects should be accounted for when $Q_{rad} = \sigma (T_{max}^4 - T_{min}^4)$ is of equal or greater magnitude than that of convective and conductive heat transfer rates.
- To account for radiation, radiative intensity transport equations (RTEs) are solved.
  - Local absorption by fluid and at boundaries couples these RTEs with the energy equation.
- Radiation intensity, I(r,s), is directionally and spatially dependent.
- Transport mechanisms for radiation intensity:
  - Local absorption
  - Out-scattering (scattering away from the direction)
  - Local emission
  - In-scattering (scattering into the direction)
- Five radiation models are available in FLUENT.
  - Discrete Ordinates Model (DOM)
  - Discrete Transfer Radiation Model (DTRM)
  - P1 Radiation Model
  - Rosseland Model
  - Surface-to-Surface (S2S)



Discrete Ordinates Model

- The radiative transfer equation is solved for a discrete number of finite solid angles, σ_s:

$$\frac{\partial I}{\partial x_i} + \underbrace{(a + \sigma_s)\, I(r,s)}_{\text{Absorption}} = \underbrace{a\, n^2 \frac{\sigma T^4}{\pi}}_{\text{Emission}} + \underbrace{\frac{\sigma_s}{4\pi} \int_0^{4\pi} I(r,s')\, \Phi(s \cdot s')\, d\Omega'}_{\text{Scattering}}$$

- Advantages:
  - Conservative method leads to heat balance for coarse discretization.
    - Accuracy can be increased by using a finer discretization.
  - Most comprehensive radiation model:
    - Accounts for scattering, semi-transparent media, specular surfaces, and wavelength-dependent transmission using banded-gray option.
- Limitations:
  - Solving a problem with a large number of ordinates is CPU-intensive.

Discrete Transfer Radiation Model (DTRM)

- Main assumption – Radiation leaving a surface element within a specified range of solid angles can be approximated by a single ray.
- Uses a ray-tracing technique to integrate radiant intensity along each ray:

$$\frac{dI}{ds} + a\,I = \frac{a\,\sigma\,T^4}{\pi}$$

- Advantages:
  - Relatively simple model.
  - Can increase accuracy by increasing number of rays.
  - Applies to wide range of optical thicknesses.
- Limitations:
  - Assumes all surfaces are diffuse.
  - Effect of scattering not included.
  - Solving a problem with a large number of rays is CPU-intensive.

P-1 Model

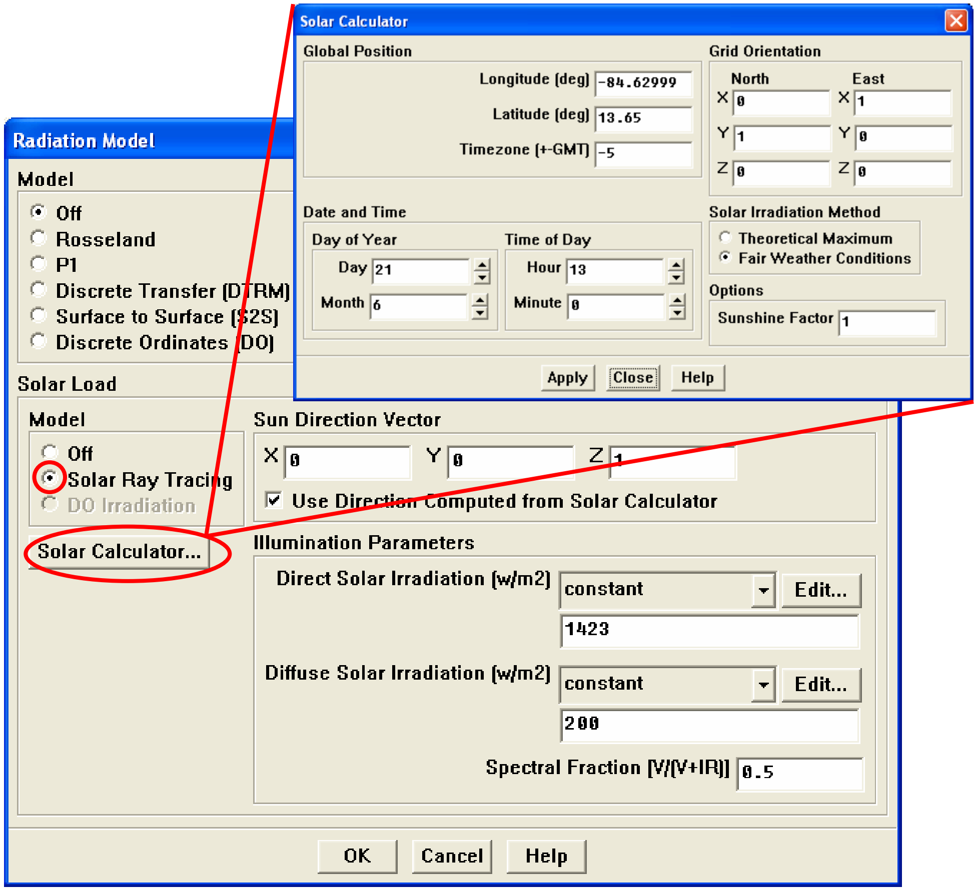
- Main assumption – The directional dependence in RTE is integrated out, resulting in a diffusion equation for incident radiation.
- Advantages:
  - Radiative transfer equation easy to solve with little CPU demand.
  - Includes effect of scattering.
    - Effects of particles, droplets, and soot can be included.
  - Works reasonably well for applications where the optical thickness is large (e.g. combustion).
- Limitations:
  - Assumes all surfaces are diffuse.
  - May result in loss of accuracy (depending on the complexity of the geometry) if the optical thickness is small.
  - Tends to overpredict radiative fluxes from localized heat sources or sinks.

Surface-to-Surface Radiation Model

- The S2S radiation model can be used for modeling radiation in situations where there is no participating media.
  - For example, spacecraft heat rejection system, solar collector systems, radiative space heaters, and automotive underhood cooling.
  - S2S is a view-factor based model.
  - Non-participating media is assumed.
- Limitations:
  - The S2S model assumes that all surfaces are diffuse.
  - The implementation assumes gray radiation.
  - Storage and memory requirements increase very rapidly as the number of surface faces increases.
    - Memory requirements can be reduced by using clusters of surface faces.
      - Clustering does not work with sliding meshes or hanging nodes.
  - Not to be used with periodic or symmetry boundary conditions.

Solar Load Model

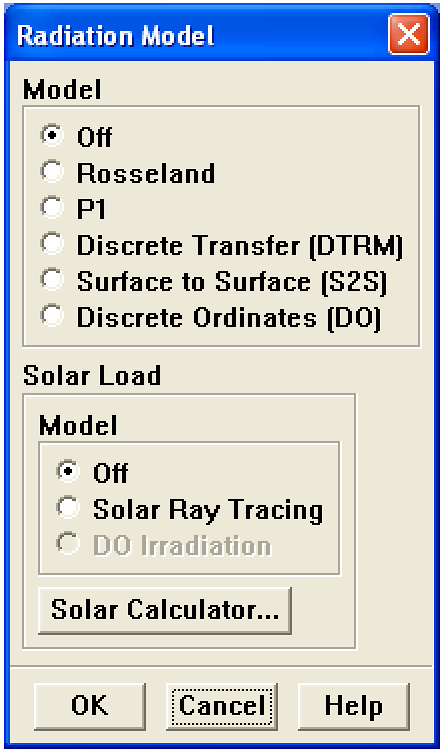
- Solar load model
  - Ray tracing algorithm for solar radiant energy transport: Compatible with all radiation models
  - Available with parallel solver (but ray tracing algorithm is not parallelized)
  - 3D only
- Specifications
  - Sun direction vector
  - Solar intensity (direct, diffuse)
  - Solar calculator for calculating direction and direct intensity using theoretical maximum or “fair weather conditions”
  - Transient cases
    - When direction vector is specified with solar calculator, sun direction vector will change accordingly in transient simulation
    - Specify “time steps per solar load update”



Choosing a Radiation Model

- For certain problems, one radiation model may be more appropriate in general.
  - Computational effort – P1gives reasonable accuracy with less effort.
  - Accuracy – DTRM and DOM more accurate.
  - Optical thickness – DTRM/DOM for optically thin media ($\alpha L << 1$); P1 better for optically thick media.
  - Scattering – P1 and DOM account for scattering.
  - Particulate effects – P1 and DOM account for radiation exchange between gas and particulates.
  - Localized heat sources – DTRM/DOM with sufficiently large number of rays/ ordinates is more appropriate.

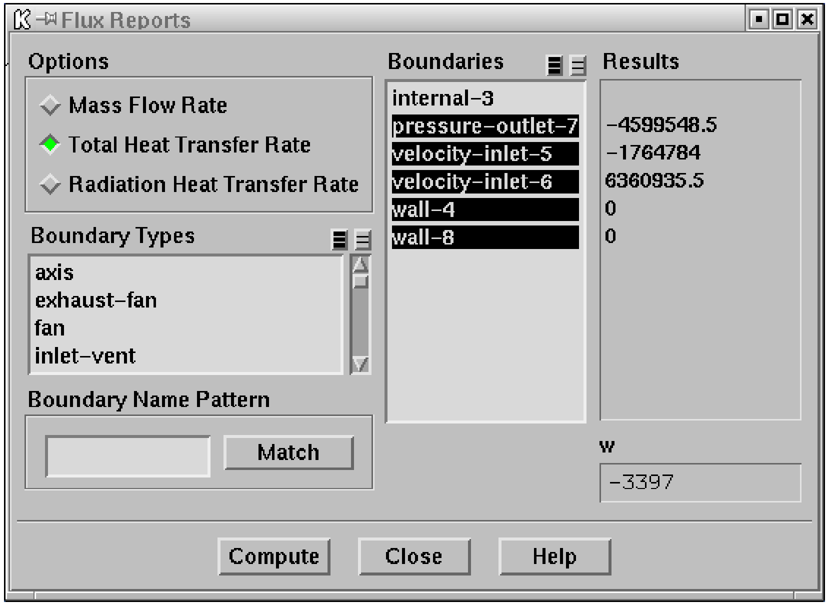
Define → Models → Radiation...



Reporting – Heat Flux

- Heat flux report:
  - It is recommended that you perform a heat balance check to ensure that your solution is truly converged.
- Exporting Heat Flux Data:
  - It is possible to export heat flux data on wall zones (including radiation) to a generic file.
  - Use the text interface:
    file/export/custom-heat-flux
  - File format for each selected face zone:

```
zone-name nfaces
x_f  y_f  z_f  A  Q  T_w  T_c  HTC
...
```



Reporting – Heat Transfer Coefficient

- Wall-function-based HTC

$$h_{\text{eff}} = \frac{\rho\, C_P\, C_\mu^{1/4}\, k_P^{1/2}}{T^*}$$

where C_P is the specific heat, k_P is the turbulence kinetic energy at point P, and T^* is defined in Chapter 13 of the FLUENT 6.3 User Guide.

- Available only when the flow is turbulent and Energy equation is enabled
- Alternative for cases with adiabatic walls.

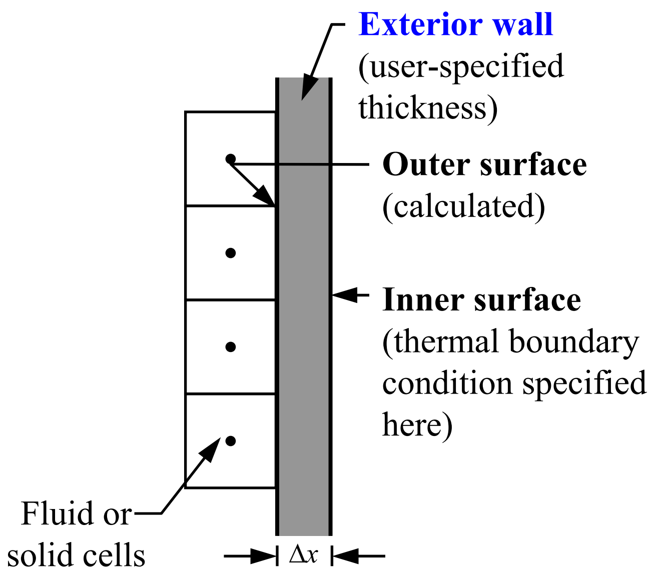
Summary

- There are many introductory level tutorials which use concepts discussed in this lecture.
  - Periodic Flow and Heat Transfer (Tutorial #2)
  - Radiation and Natural Convection (Tutorial #5)
  - Solidification (Tutorial #20)
  - Many others…
- A number of intermediate and advanced tutorials are also available at www.learningcfd.com/login/fluent/intermediate/tutorials/index.htm
- Other learning resources
  - Advanced training course in heat transfer offered by FLUENT
  - Web-based training modules
  - User Services Center, www.fluentusers.com
    - All tutorials and lecture notes
    - User Documentation

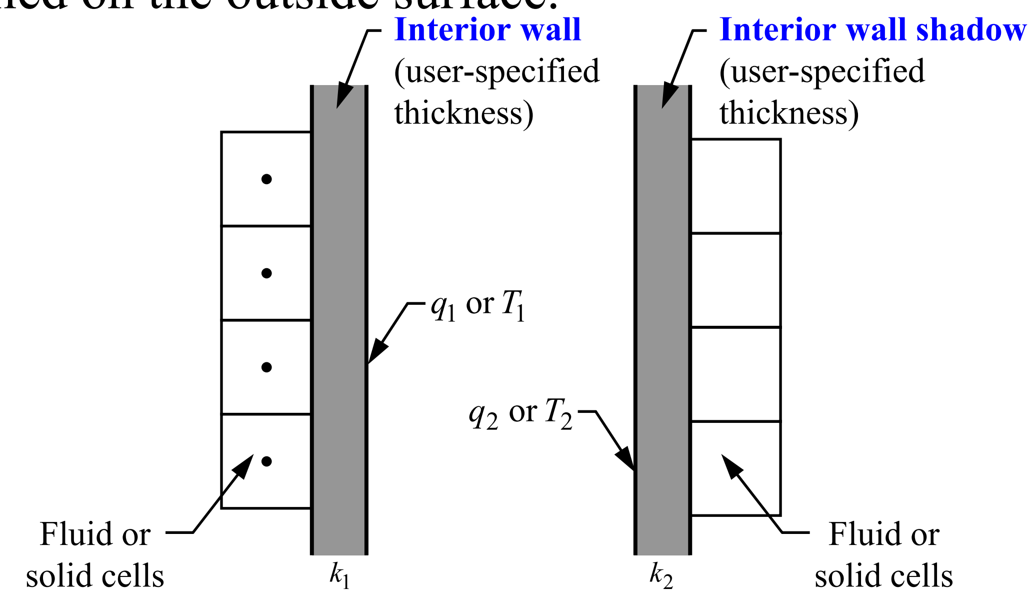
Appendix

Thin and Two-Sided Walls

- In the Thin Wall approach, the wall thickness is not explicitly meshed.
- Model thin layer of material between two zones
- Thermal resistance Δx/k is artificially applied by the solver.
- Boundary conditions specified on the outside surface.



Thermal boundary conditions are supplied on the inner surface of a thin wall

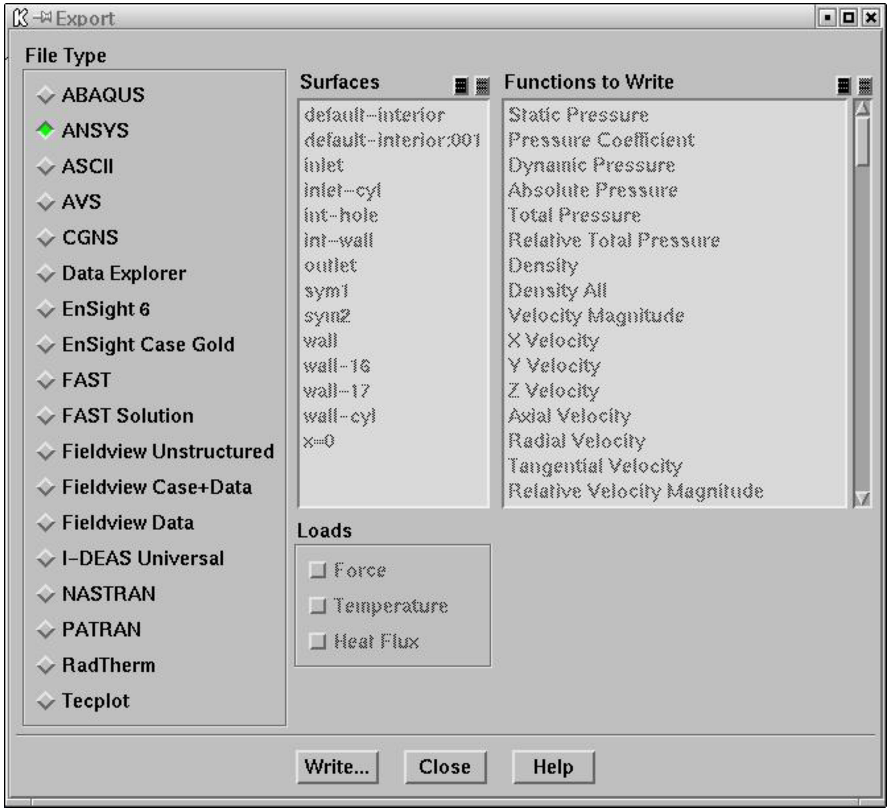


Thermal boundary conditions are supplied on the inner surfaces of uncoupled wall/shadow pairs

Export – ANSYS

- Export ANSYS file through GUI or TUI:
  `file/export/ansys` *`file-name`*

- A single file will be written containing coordinates, connectivity, and the scalars listed below:
  - x-velocity, y-velocity, z-velocity, pressure, temperature,
  - turb-kinetic -energy, turb-diss-rate, density, viscosity-turb, viscosity-lam, viscosity-eff, thermal-conductivity-lam, thermal-conductivity-eff,
  - total-pressure, total-temperature, pressure-coefficient, mach-number, stream-function,
  - heat-flux, heat-transfer-coef, wall-shear, specific-heat-cp



Export – ANSYS

- The file written is an ANSYS results file with a .rfl extension. To read this file into ANSYS, use the following procedure:

1. In ANSYS, go to General Postproc Data and File Options and read the .rfl file generated from FLUENT.
2. Go to Results Summary and click on the first line in the upcoming panel. You will see some information listed in the ANSYS_56_OUTPUT window displaying geomtery informatiom.
3. In the small ANSYS Input window, enter the following commands in order:

   ```
   SET,FIRST
   /PREP7
   ET,1,142
   ```

   The last command corresponds to FLOTRAN 3D element. If your case is 2D, then this should be replaced by "**ET,1,141**".
4. In the ANSYS MULTIPHYSICS UTITLITY menu, select Plot and then Nodes or Elements, including the nodal solution under Results in the drop-down list.

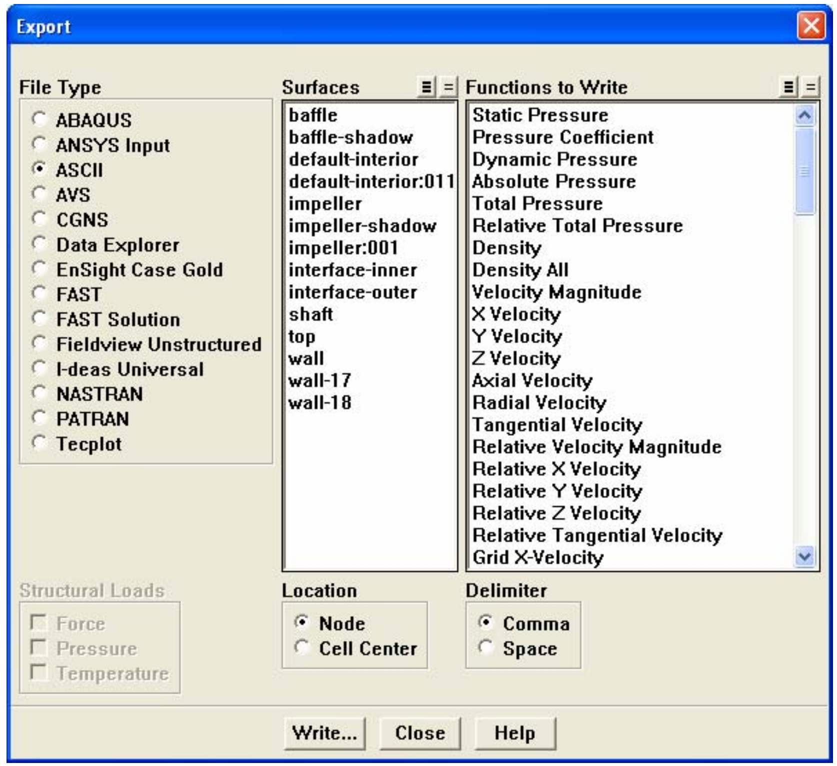
Export – ABAQUS

- A single file (e.g., file.aba) containing coordinates, connectivity, optional loads, zone groups, velocity, and selected scalars will be written. You can specify which scalars you want in the Functions to Write list.
- Export of data to Abaqus is available only for 3D models and is valid only for solid zones or for those surfaces that lie at the intersection of solid zones.
- None of the fluid zone heat transfer properties will get exported
- Ideal only when you want to do some Fluid-Solid interface i.e., wall analysis.

`file/export/abaqus` ***`file-name list-of-surfaces`*** () yes|no ***`list-of-scalars`*** q

Export to Other Formats

- NASTRAN/PATRAN: The best approach.
- For ABAQUS, NASTRAN, and PATRAN, select the Loads to be written (Force, Temperature, and/or Heat Flux) to analyze the structural stresses (fluid pressure or thermal) in an FEA program.
- Loads are written only on boundary walls when the entire domain is exported (i.e., if you select no Surfaces).



Format	Supported Version
Abaqus	6.3
ANSYS	10
ASCII	n/
CGNS	2
NASTRAN	2001
PATRAN	2001
TECPLOT	9