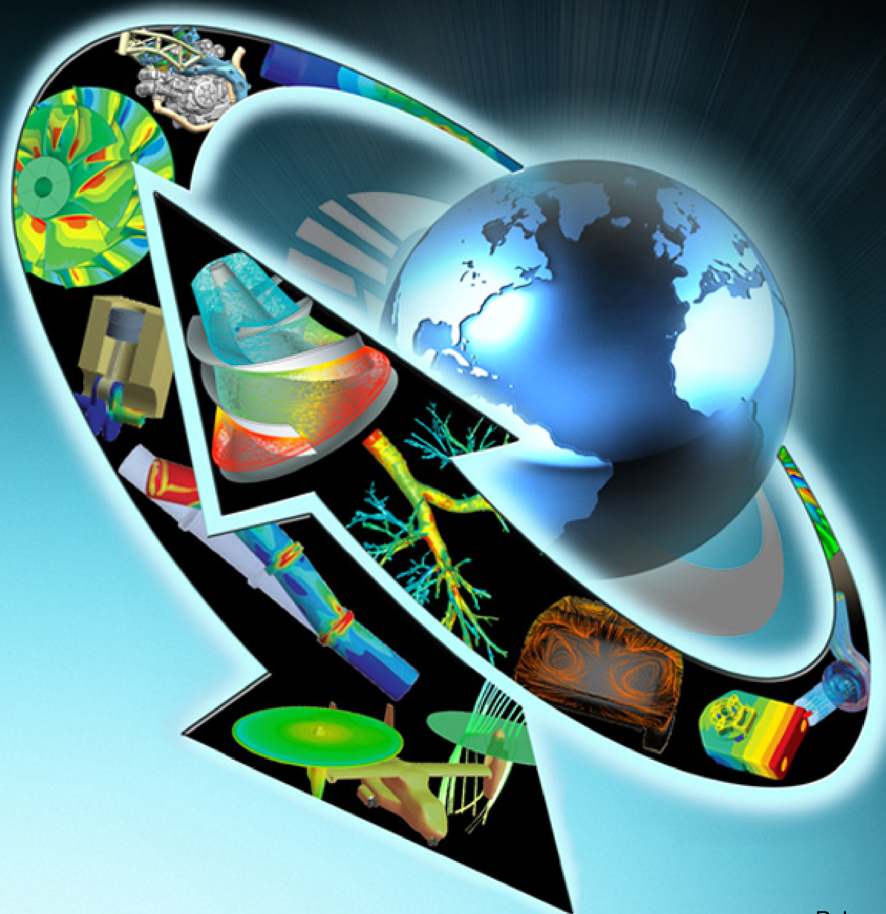
Customer Training Material

Lecture 5

Radiation Heat Transfer

Heat Transfer Modeling using ANSYS FLUENT



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Outline

- Radiation modeling theory
- Radiation models in FLUENT
  - Surface-to-Surface (S2S)
  - Discrete Ordinates (DO)
  - Discrete Transfer Radiation Model (DTRM)
  - P-1
  - Rosseland
- Selecting a radiation model
- Postprocessing
- Conclusions
- Appendix

Introduction

- Thermal radiation is emission of energy as electromagnetic waves.
  - Thermal radiation can occur in vacuum
  - When any object is above absolute zero it emits energy.

- Industrial applications for which FLUENT's radiation models are used:
  - Combustion (gas turbine, boilers, rocket engine, glass furnace, steel reheat furnace)
  - Automotive under-hood
  - Heating, Ventilation, and Air-Conditioning (HVAC)
  - Headlights
  - Ultraviolet disinfection (water treatment)
  - Glass applications (forming, glass tank)
  - Many other high-temperature applications

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- **Radiation models in FLUENT**
  - **Surface-to-Surface (S2S)**
  - Discrete Ordinates (DO)
  - Discrete Transfer Radiation Model (DTRM)
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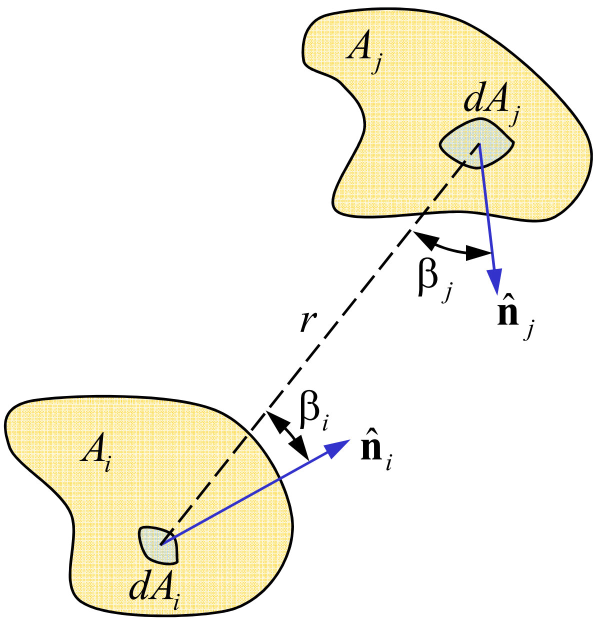
Surface to Surface (S2S) Model

- **Method for non-participating media only**
  - **Only surfaces radiate (zero optical thickness).**
- **Method based on view factor calculation (Chaparral)**
  - **N equations for N surfaces which can be cast into matrix form as**



$$[K]\{J\}=\{E\}$$

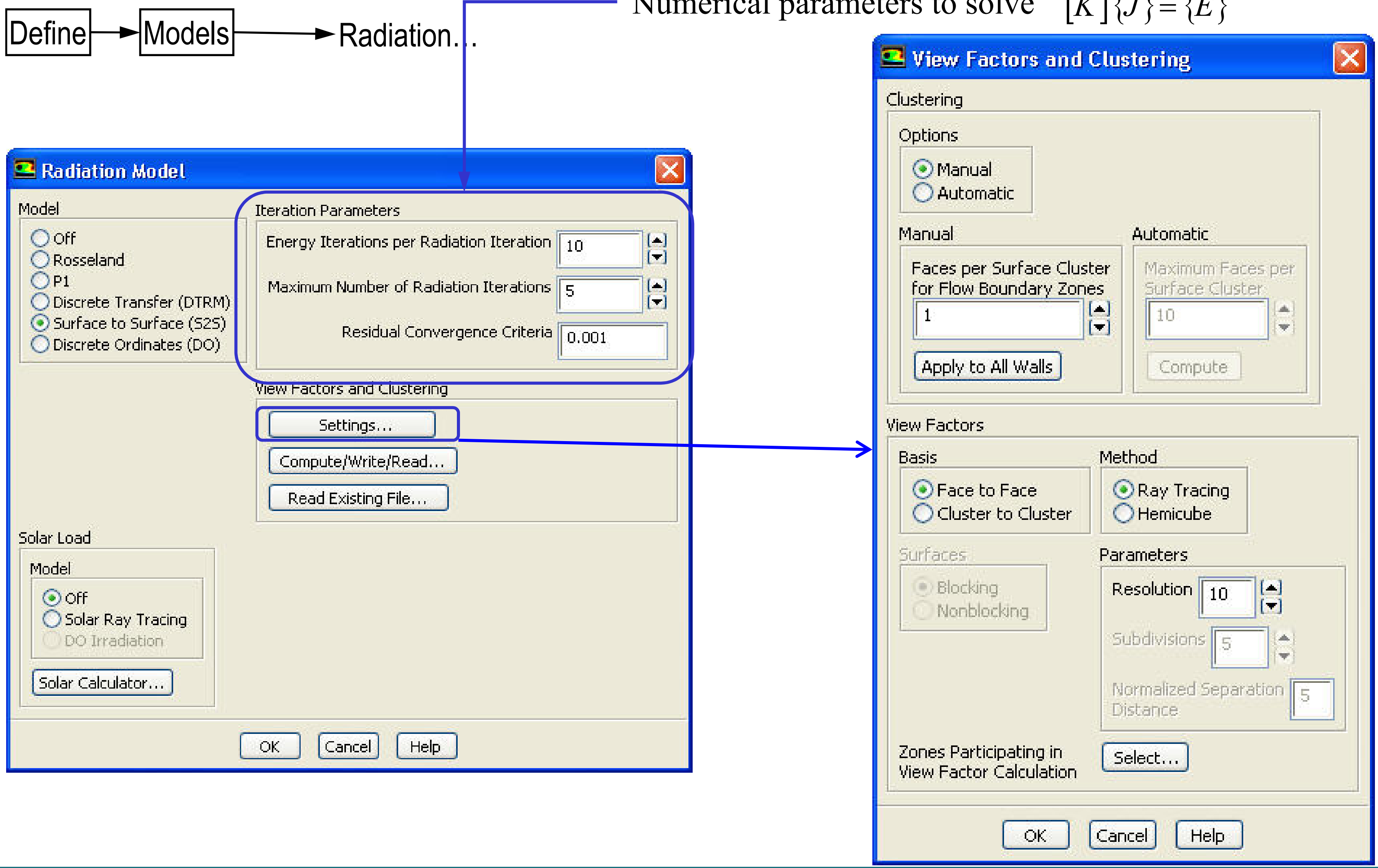
- $[K]$: N×N matrix
- $\{J\}$: Radiosity vector
- $\{E\}$: Emissive power vector

$$F_{ij}=\frac{1}{A_i}\int_{A_i}\int_{A_j}\frac{\cos\beta_i\,\cos\beta_j}{\pi\,r^2}\,\delta_{ij}\,dA_j\,dA_i$$

F_{ij}: View Factor; fraction of the diffuse radiative energy leaving surface i and arriving at surface j

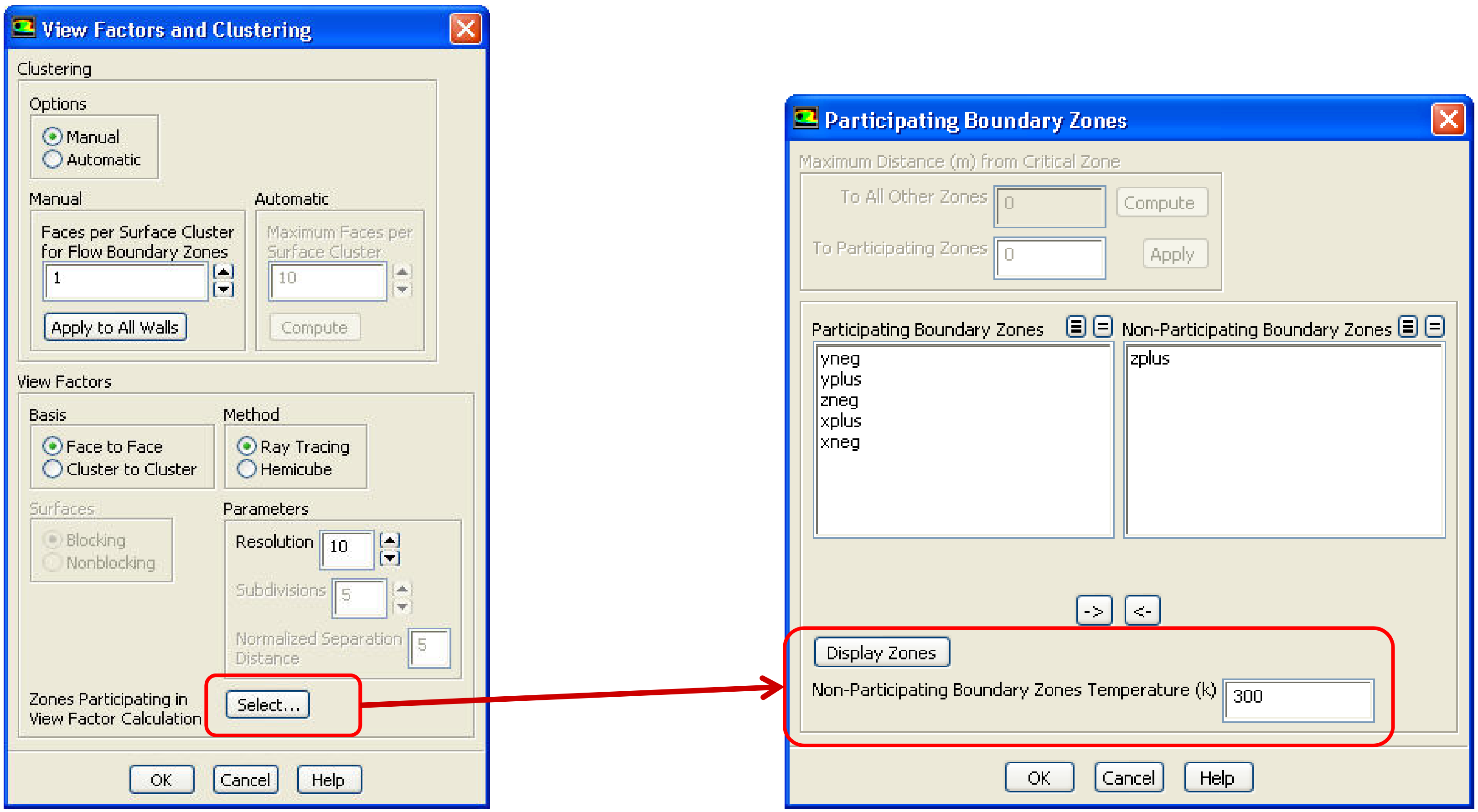
S2S Model Setup

Numerical parameters to solve $[K]\{J\}=\{E\}$

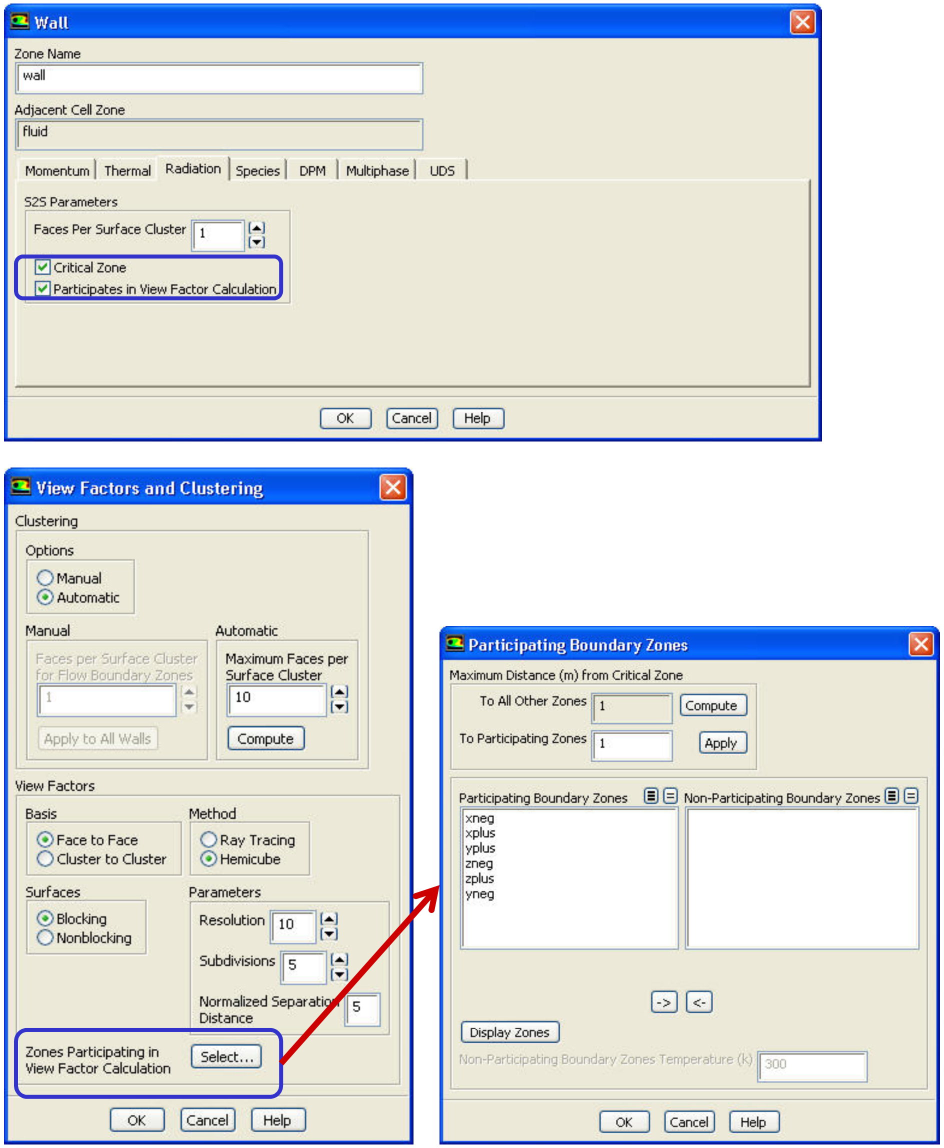


S2S – Partial Enclosure Option

- **Before performing view factor calculation, deselect surfaces that you don't need in your view factor calculation**
- **Unselected surfaces are regarded as black body at the temperature defined in the Participating Boundary Zones panel.**



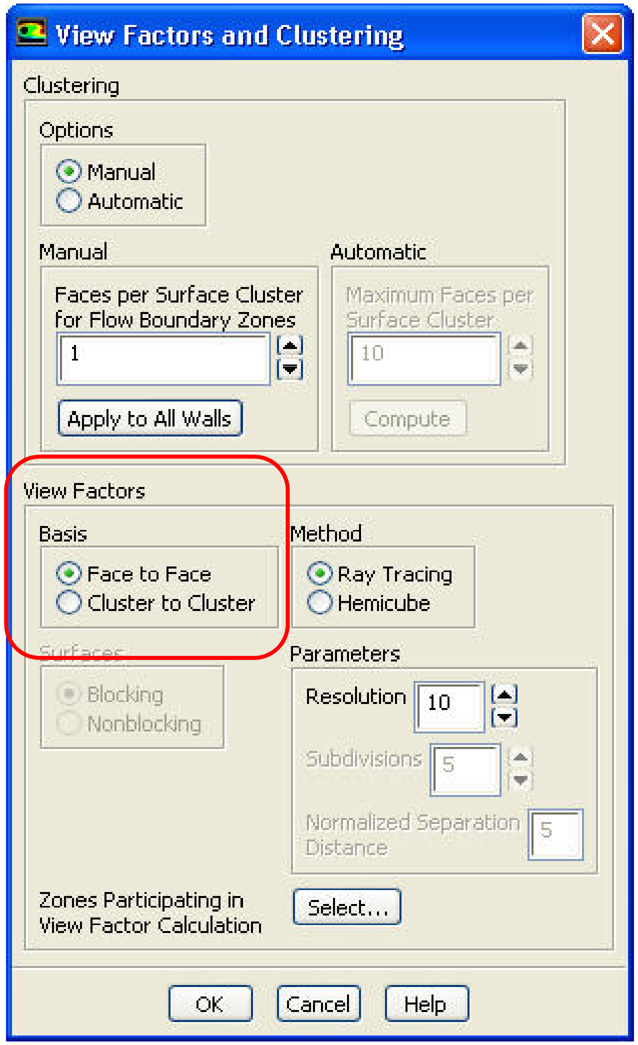
S2S – Partial Enclosure Option 2



- **Critical zone: Boundary zone in which radiation is very important**
- **Select Automatic option first.**
- **Define the Critical Zone in boundary condition panel**
- **Compute maximum of distances between critical zone and other zones**
- **Enter maximum distance of participating zone and the critical zone.**
- **All zones having a critical zone distance greater than the specified distance will be made non-participating**

Parameters for View Factor Calculation

- **Face to Face**
  - By default, view factors are calculated using a face to face basis.
  - The boundary faces act as the surfaces for the view factor calculation, and then a cluster view factor is obtained by taking the area-weighted average of the view factors of the faces within the cluster.
- **Cluster to Cluster**
  - Only in 3D
  - Reduces the computational expense and storage requirements.
  - ANSYS FLUENT internally creates polygon faces by combining all of the faces from non-polyhedral cells in each cluster, and these are then used as the surfaces for the view factor calculation.
  - Less accurate



Parameters for View Factor Calculation

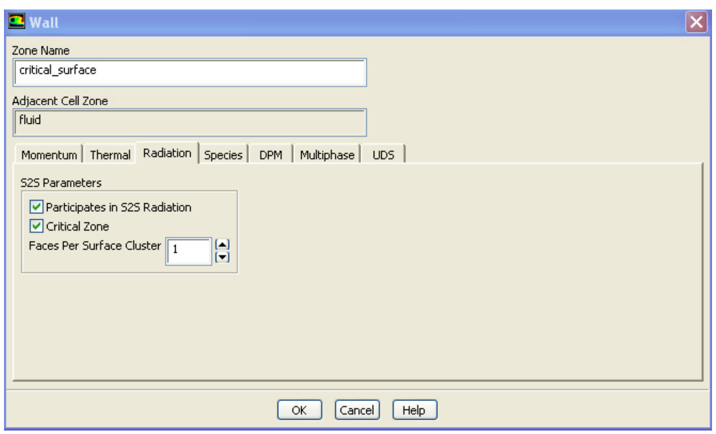
- Clustering is the built-in capability to group surface faces
- Use fewer surface faces for radiation calculation than flow calculation.
- Reduces only the size of the view factor file
- Calculation process is not faster

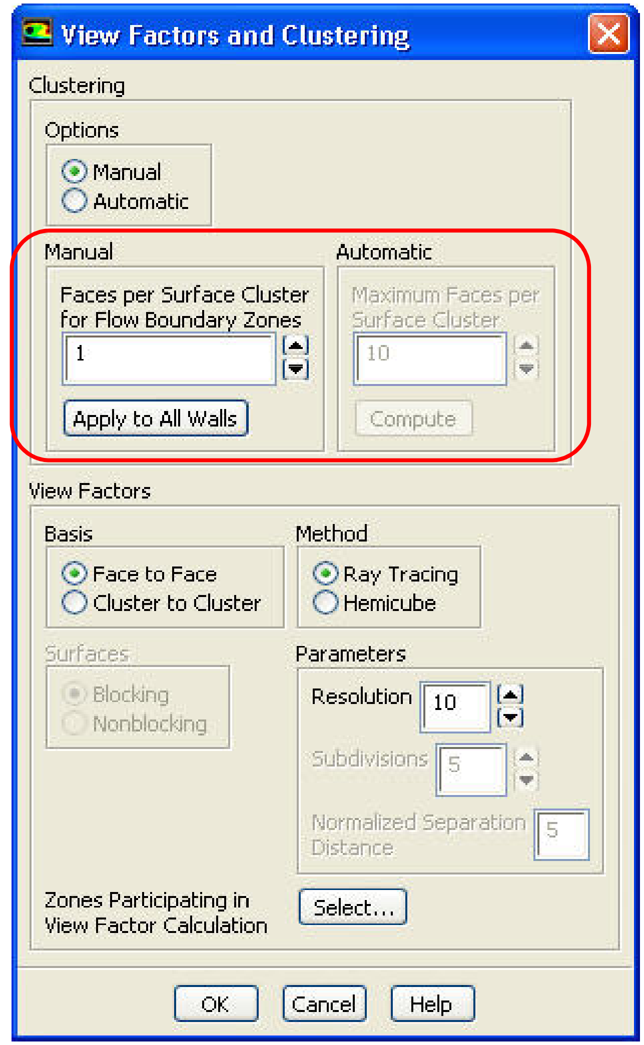
Manual

- Faces per surface cluster (FPSC) can be easily specified and applied to all zones
- Any modifications to the FPSC in the critical and non-critical zones need to be done manually.

Automatic

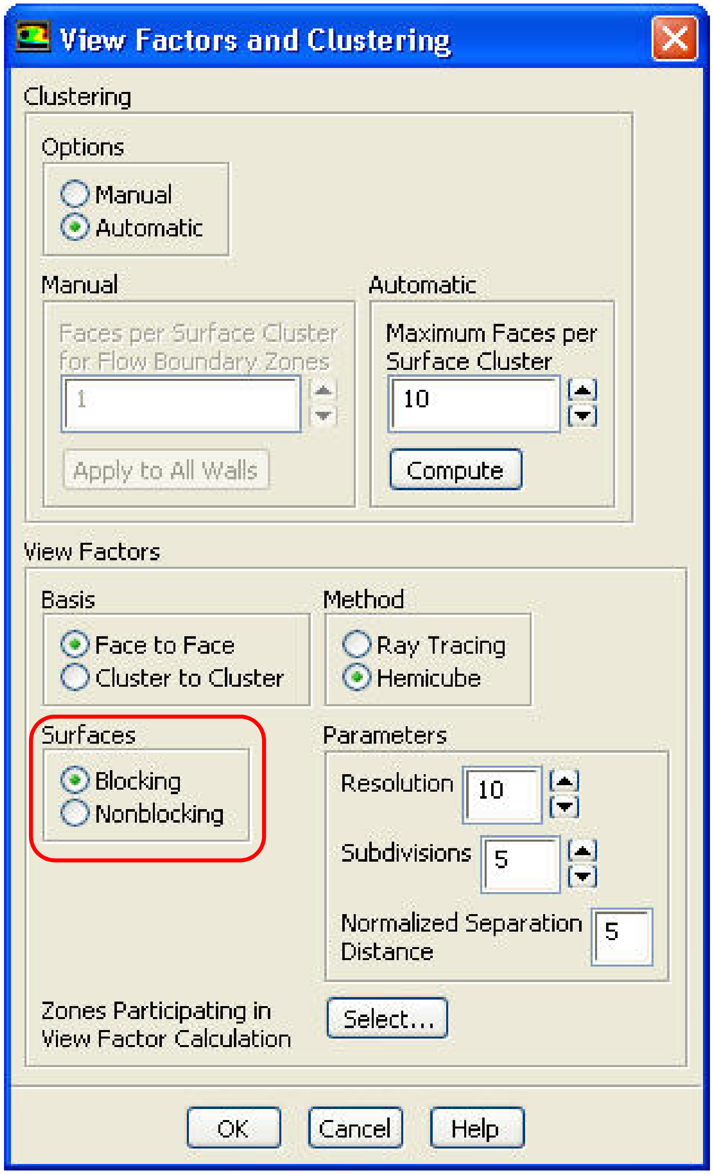
- Calculates FPSC values automatically based on the distance of the zones from other critical zones
- Define the critical zone and specify the minimum FPSC





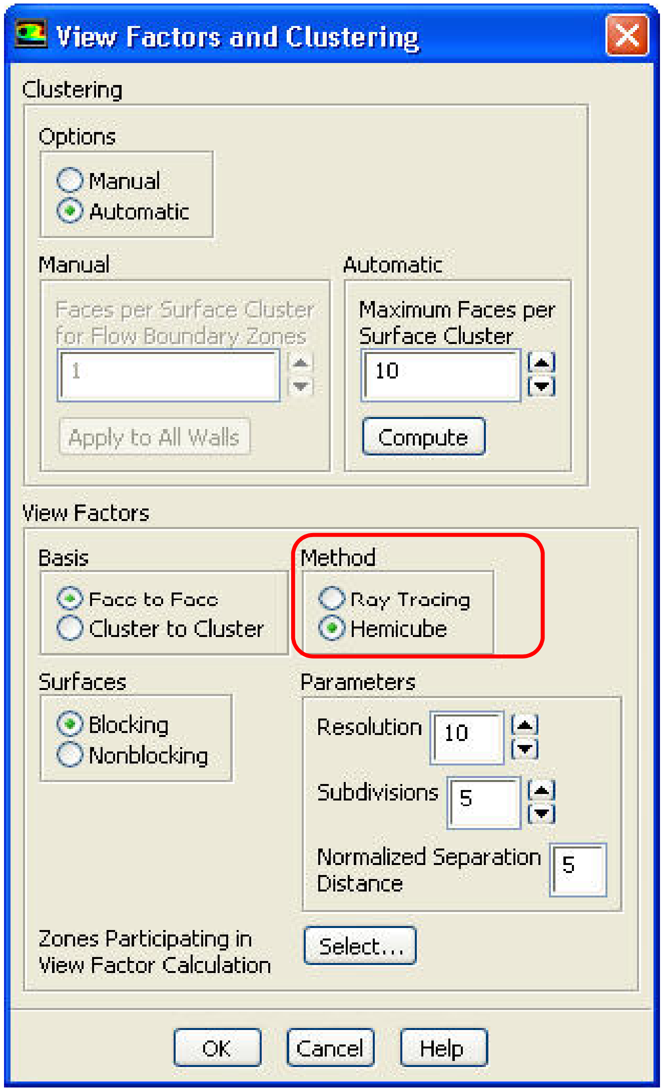
Parameters for View Factor Calculation

- **Blocking / Nonblocking:**
  - **If there is no obstruction between the surface pairs under consideration, then they are referred to as "non-blocking" surfaces.**
  - **If there is another surface blocking the views between the surfaces under consideration, then they are referred to as "blocking" surfaces. Blocking will change the view factors between the surface pairs and require additional checks to compute the correct value of the view factors.**



Parameters for View Factor Calculation

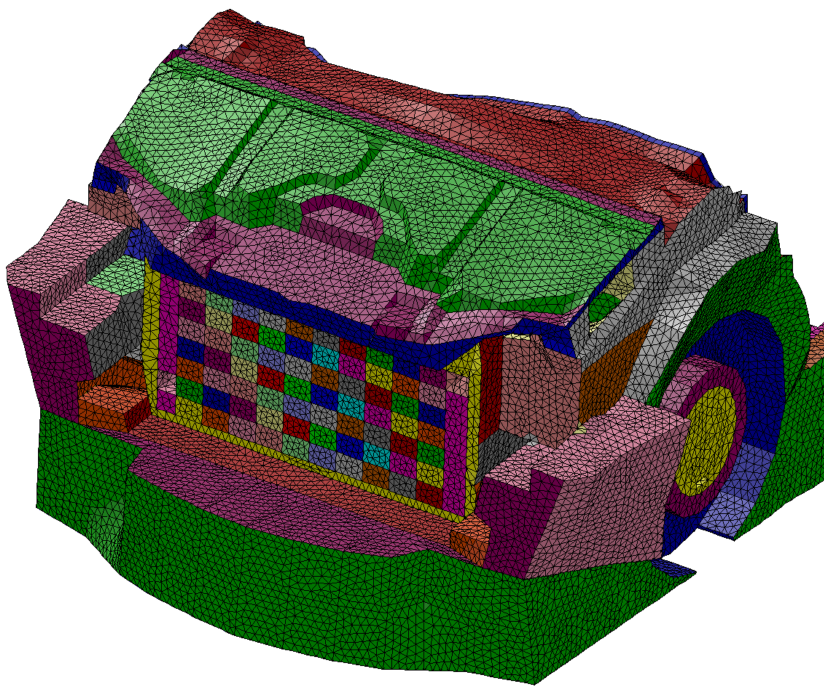
- **Hemicube**
  - It should be used for complex 3D geometries with few obstructing surfaces between the radiating faces.
- **Ray Tracing**
  - Is parallelized and should therefore be employed in complex 3D geometries with lots of obstructing surfaces such as automotive underhood simulations.

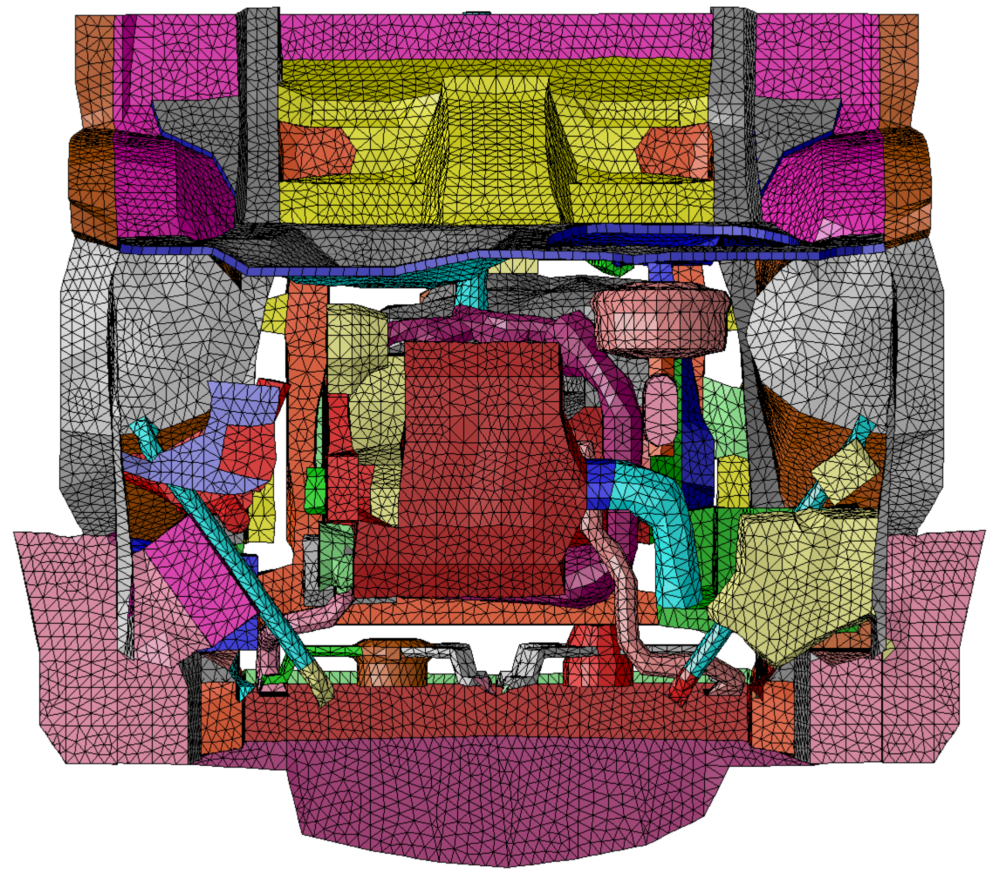


Advantages and Disadvantages of S2S

- Advantages
  - Once View-Factor calculation is done, low time per iteration
  - View-factor calculation is possible in the parallel solver
  - Much better accuracy in cases of localized heat sources than DO or any ray-tracing method
  - Much smaller memory usage and file storage
- Disadvantages
  - The S2S model assumes that all surfaces are diffuse
  - The implementation assumes gray radiation
  - The storage and memory requirements increase very rapidly as the number of surface faces increases (N x N)
  - CPU time is independent of the number of clusters used
  - Cannot be used to model participating radiation problems
    - Scattering, emission, absorption
  - Cannot be used with periodic boundary conditions
  - Hemicube view factor methods cannot be used with symmetry boundary conditions
  - Does not support non-conformal interfaces, hanging nodes or mesh adaption
  - Not strictly conservative

S2S Example – Under-Hood Thermal Modeling

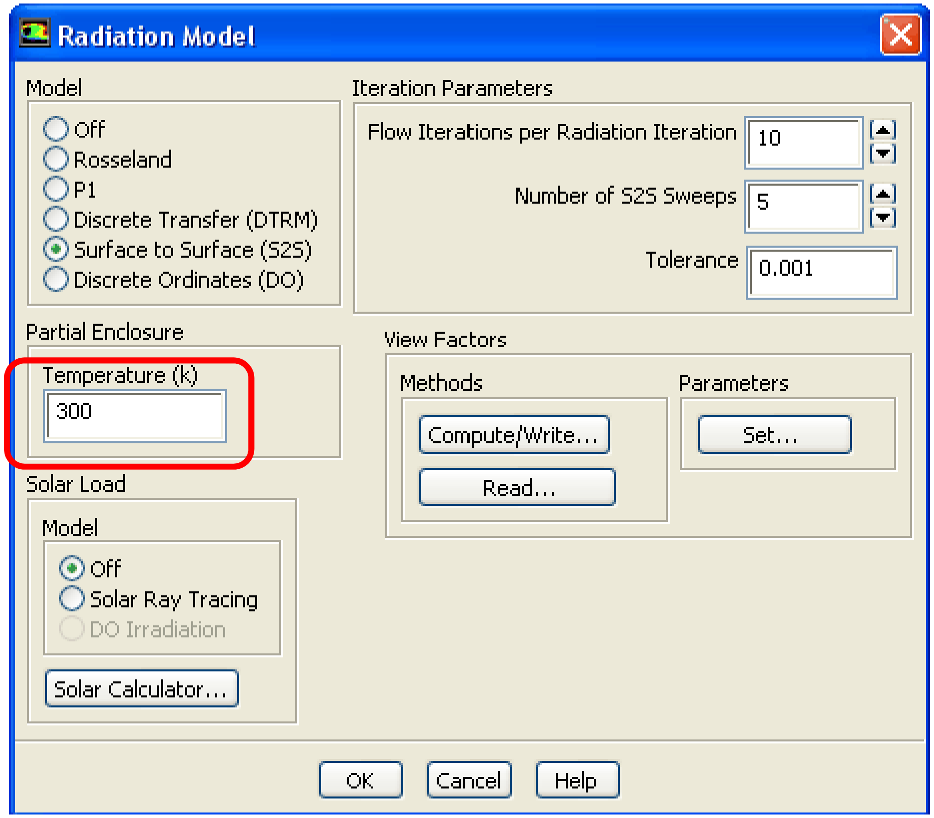




441,929 tets
58,550 shells
Total: 500,479 cells
89,497 boundary faces

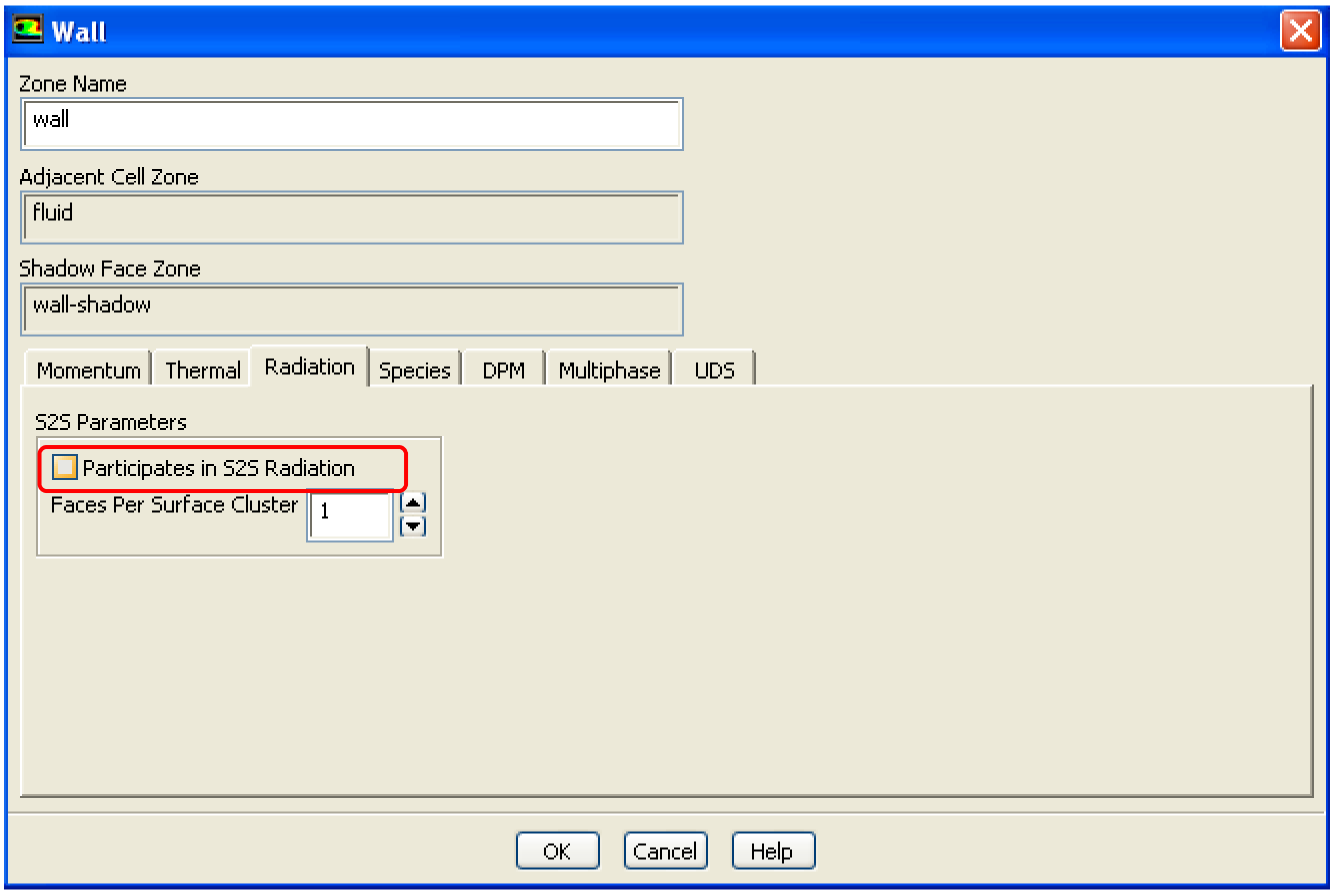
S2S Example – Under-Hood Thermal Modeling

- **STEP 1: Making Partial Enclosure**
  - **Identify those components that have temperature close to "Partial Enclosure Temperature"**
  - **Setting Partial Enclosure Temperature**

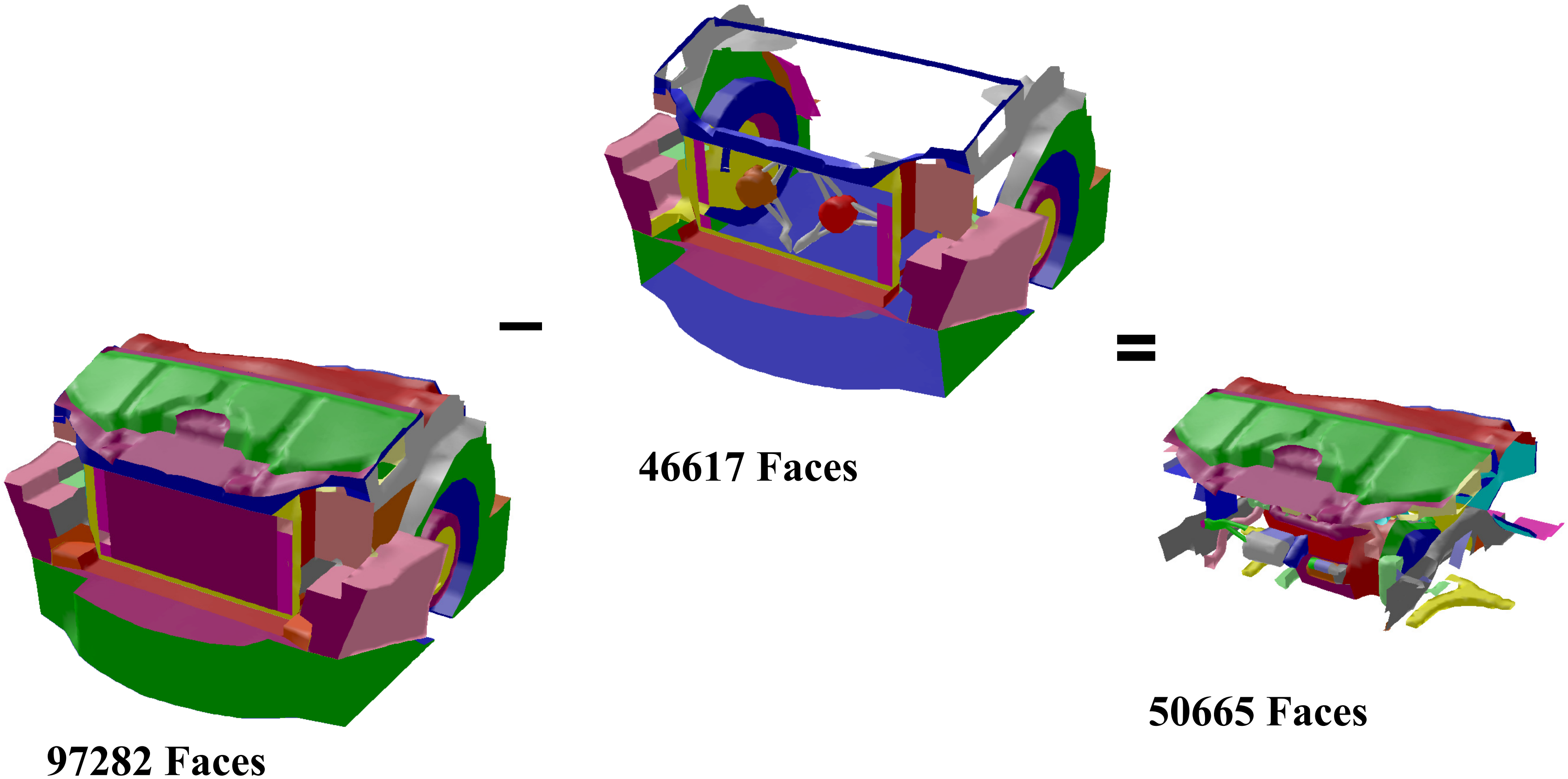


S2S Example – Under-Hood Thermal Modeling

- **STEP 1: Making Partial Enclosure**
  - **Toggle off Participates in S2S Radiation in all the walls (including shadows) that are part of partial enclosure.**

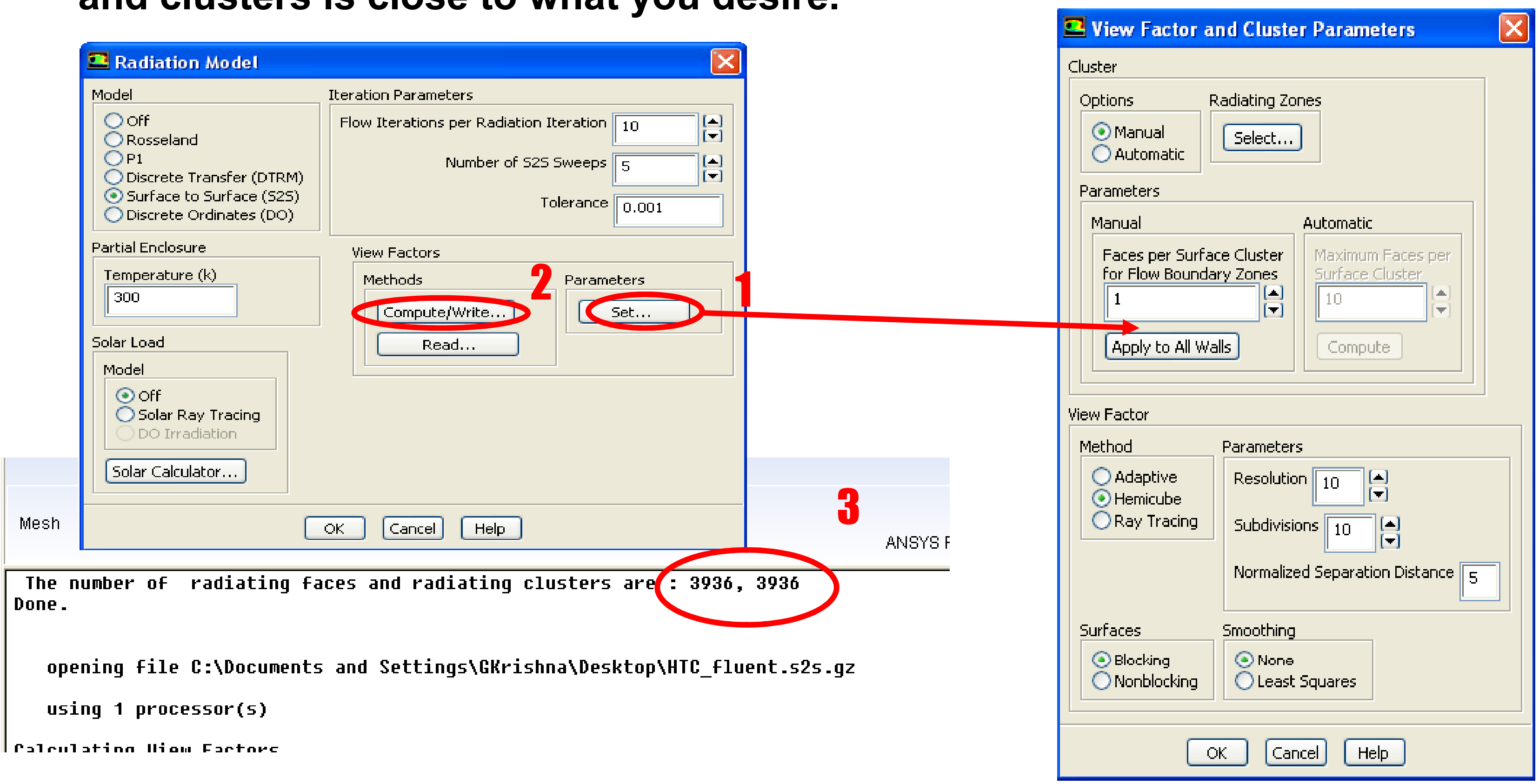


S2S Example – Under-Hood Thermal Modeling



S2S Example – Under-Hood Thermal Modeling

- **STEP 2: Calculate view factors (within FLUENT)**
- **Calculate the cluster file:** File → Write → Surface Clusters…
  - **Specify Faces Per Surface Cluster**
  - **Set Method to Hemicube**
    - **After writing, make sure ratio of radiating faces and clusters is close to what you desire.**



Computing View Factors Outside FLUENT

- **Set parameters in the View Factor & Cluster Parameters panel.**
- **Write cluster information to a file.**
  - **Serial solver**

    `viewfac` ***cluster-file***
  - **Parallel solver**

    `viewfac -t`***n*** ***cluster-file***
  - **Parallel network solver:**

    `viewfac -p -tn` ***host1*, *host2*, …, *hostn* *cluster-file***
- **Read the view-factor file into FLUENT in the Radiation Model panel.**

S2S Example – Under-Hood Thermal Modeling

- **STEP 3: Solve**
  - Obtain cold-flow solution (first-order, then second-order). Default under-relaxation should be adequate
  - Increase Under-Relaxation for Energy to 1.0
  - Iterate to convergence
  - If Density is not constant:
  - Freeze temperature field and solve for flow
  - Freeze flow field and solve for energy
  - Repeat last two steps until there is no change in residuals or monitored temperatures

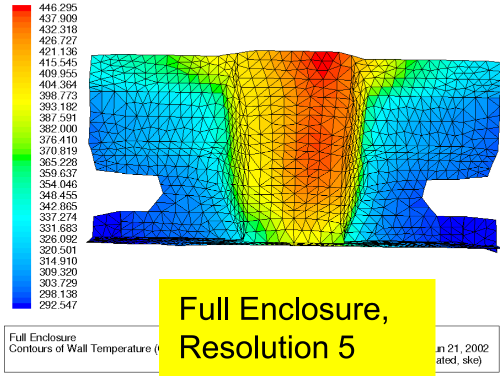
- **REMEMBER: If view factors calculated outside of FLUENT, you must read in view factors before solving. (File→Read→View Factors)**

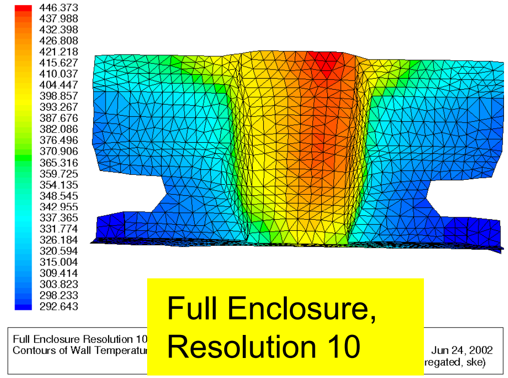
Underhood Example – Comparison of S2S and DO

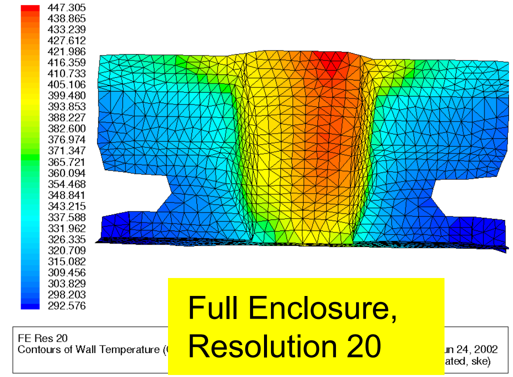
- **S2S model temperature predictions comparable to DO (3x3)**

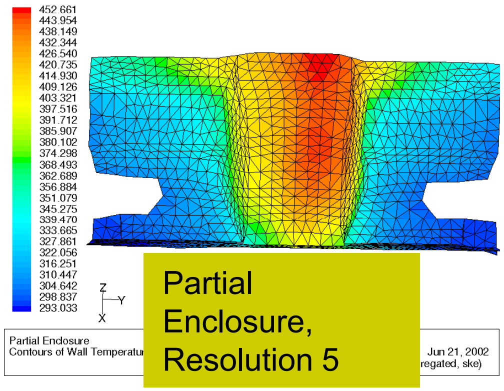
- **Advantages of S2S over DO (3x3)**
  - **S2S is 3.6 times faster (time/iteration)**
  - **67% fewer iterations**
  - **50% less RAM required**
  - **20% less storage required**

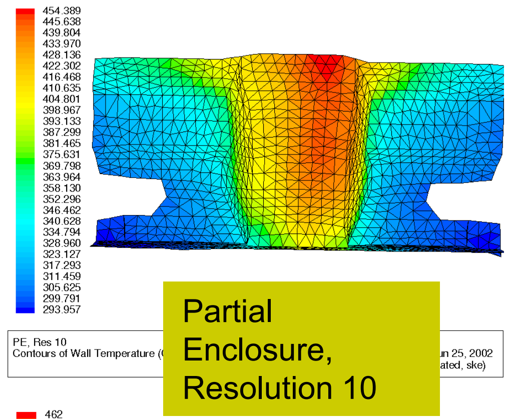
Model	Time for View Factor Calculation	RAM (MB)	Time/Iter/CPU (seconds)
S2S	4.38 hrs (3 CPUs)	1,637	556
DO (2×2)	N/A	2,422	959
DO (3×3)	N/A	3,481	1987

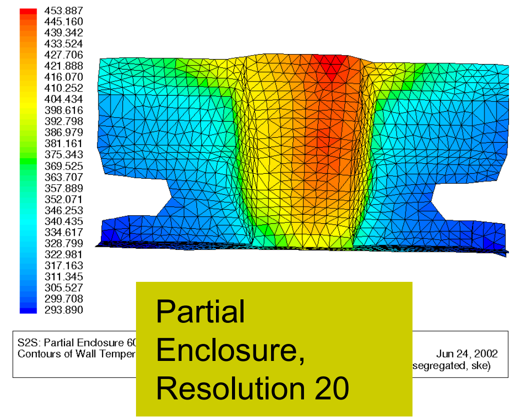

Full Enclosure
Contours of Wall Temperature
Full Enclosure, Resolution 5

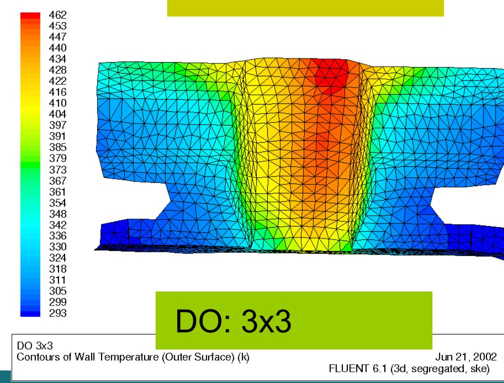

Full Enclosure Resolution 10
Contours of Wall Temperature
Jun 24, 2002
Full Enclosure, Resolution 10


FE Res 20
Contours of Wall Temperature
Full Enclosure, Resolution 20


Partial Enclosure
Contours of Wall Temperature
Jun 21, 2002
Partial Enclosure, Resolution 5


PE, Res 10
Contours of Wall Temperature
Partial Enclosure, Resolution 10


S2S: Partial Enclosure
Contours of Wall Temper
Jun 24, 2002
Partial Enclosure, Resolution 20


DO 3x3
Contours of Wall Temperature (Outer Surface) (k)
Jun 21, 2002
FLUENT 6.1 (3d, segregated, ske)
DO: 3x3

Participating Media

- **In absorbing media, it is necessary to take into account some additional terms in the energy equation**

$$\frac{\partial(\rho\,\varepsilon)}{\partial t}+\nabla\cdot\left[\mathbf{V}\,\rho\,E\right]=\nabla\cdot\left[k\,\nabla T\right]+\mathbf{q}_r$$

- **The source term depends on the incident radiation G (sum of each radiation intensity from all the direction over the whole solid angle)**

$$\nabla\cdot\mathbf{q}_r=a\,G-4\,\alpha\,\sigma\,T^4 \qquad \text{where} \qquad G=\int_{\Omega} I\,d\Omega$$

- **This characteristic implies that some additional equations have to be solved in order to include the energy source term.**
  - **G equation with P1 method**
  - **I equations (DTRM or DOM)**

Radiative Properties of Materials

- **All material properties are specified in the Materials panel.**

- **Absorption**
  - **In combusting flows, the mixture absorption coefficient accounts for the different absorptivities of the species CO_2 and H_2O and is computed using the Weighted Sum of Gray Gas Model (WSGGM).**
    - **The Domain-Based option is recommend.**
    - **The Cell-Based option is mesh-dependent and should be avoided.**
  - **Soot absorption can also be included.**
  - **The default value for the absorption coefficient is zero.**

- **Diffusion**
  - **With the DO model, a scattering coefficient and phase function are required.**
  - **Scattering is automatically included when one takes into accout radiation/particle interactions when using the Discrete Phase Model (DPM).**

Radiation

- Radiation modeling theory
- **Radiation models in FLUENT**
  - Surface-to-Surface (S2S)
  - **Discrete Ordinates (DO)**
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Discrete Ordinates (DO) Model

- **Solves the RTE for a finite number of discrete solid angles, (or directions s)**

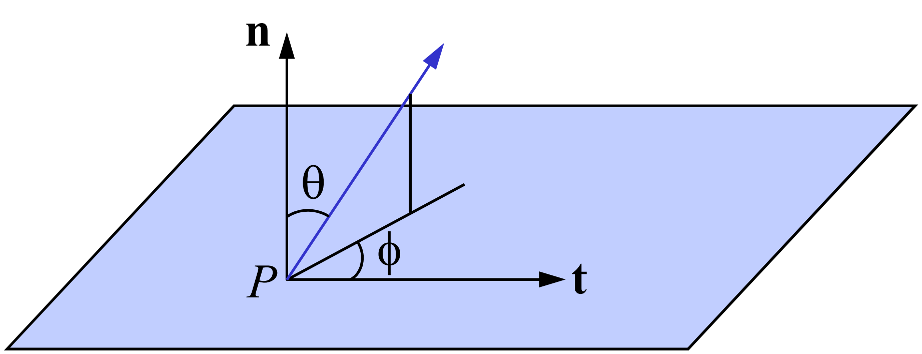
$$\nabla \cdot \left[I(\mathbf{r},\mathbf{s}) \cdot \mathbf{s} \right] + \left(a + \sigma_s \right) I(\mathbf{r},\mathbf{s}) = a\, n^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\mathbf{r},\mathbf{s}')\, \Phi(\mathbf{s} \cdot \mathbf{s}')\, d\Omega'$$

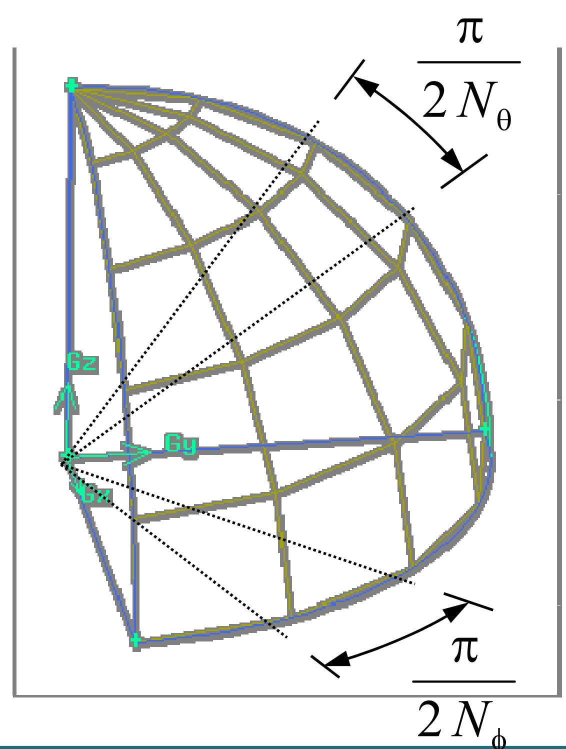
- **The RTE is written on the control volumes (existing mesh) and solved with a finite volume method as opposed to ray tracing method.**

- **Solves transport equations similar to the flow and energy equations**

DO – Angular Discretization

- Calculate in each quadrant (2D) or each octant (3D) the RTE for $N_\theta \times N_\varphi$ discrete ordinates
- Each DO has a a direction that represents the radiation within a solid angle.
- Solid angle discretization given by N_θ and N_φ
  - Azimuthal angle (φ): $0 < \varphi < 2\pi$
  - Polar angle (θ) → $0 < \theta < \pi/2$





Activating the DO Model

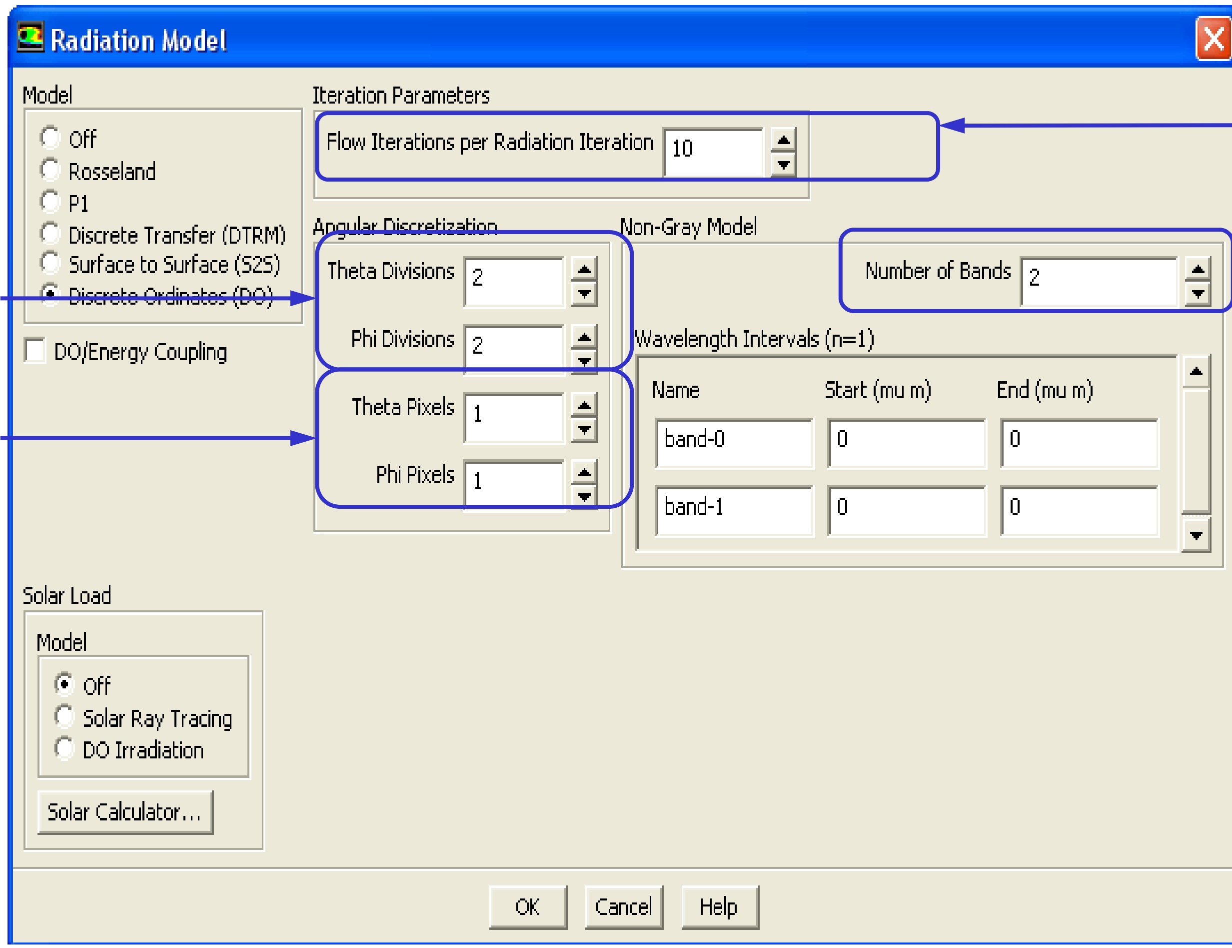
Define → Models → Radiation…

Coupling between flow + energy equation and radiation

Number of bands + interval of each spectral band

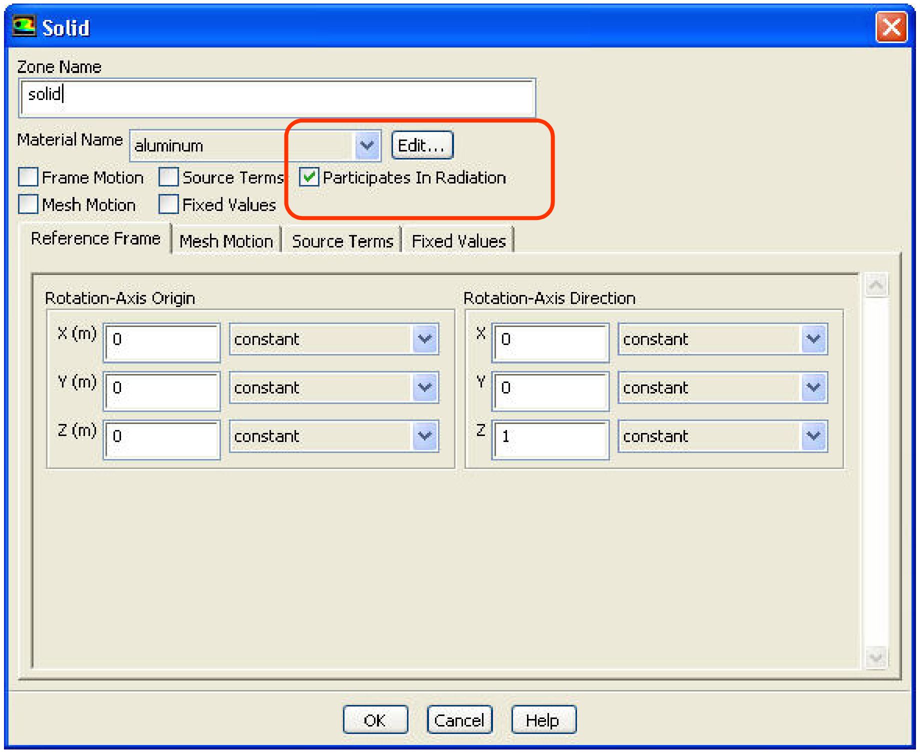
Solid angle Discretization

Pixelation



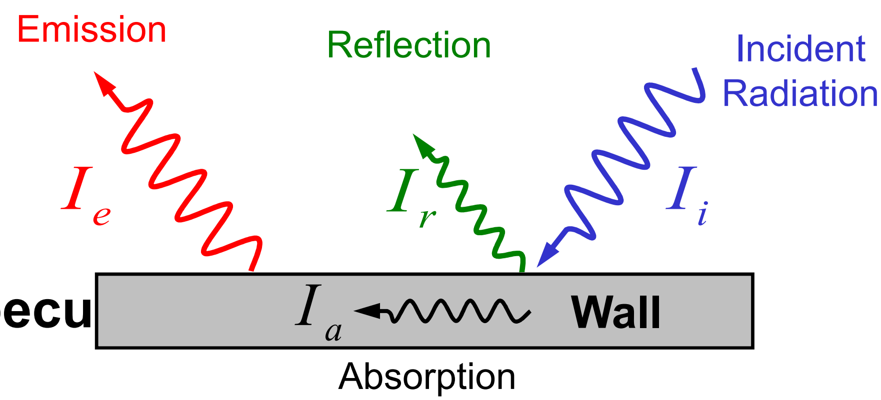
DO – Radiation in Solids

- **It is possible to compute radiation in solids (such as glass, silica, polymers, etc.)**
  - **Only a thick (meshed) wall (solid zone) will heat up when its material is absorbing radiation.**
  - **For a zero-thickness wall, absorbed energy is calculated but not dissipated. In other words, emitted energy by the volume is not accounted for.**



Properties of Opaque Surfaces

- **Reflectivity, Absorptivity, Emissivity**

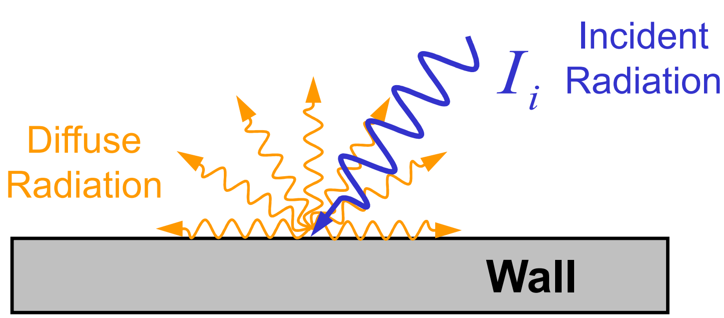


$$I_i = I_r + I_a$$

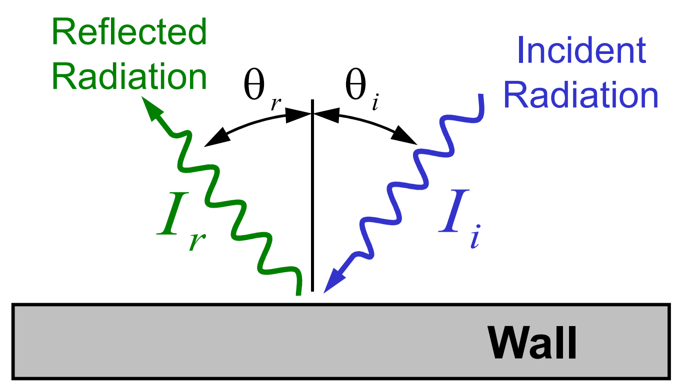
$$\rho + \alpha = 1$$

$$\alpha = \varepsilon$$

- **Specu**



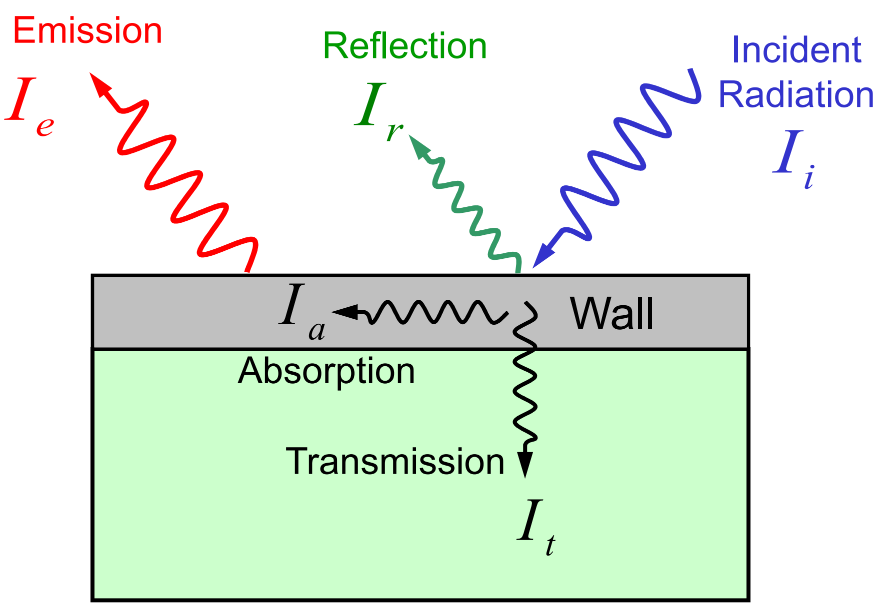
Diffuse Reflection



Specular Reflection

Semi-Transparent Surfaces

- **Reflectivity, Absorptivity, Emissivity, Transmissivity**
  - **The region into which the radiation is transmitted may or may not be part of the computational domain.**
  - **Reflection component can be either specular or diffuse.**



$$I_i = I_r + I_a + I_t$$

$$\rho + \alpha + \tau = 1$$

DO – External Semi-Transparent Walls

- **Transmitted radiation exits the computational domain**
- **Diffuse fraction between 0 and 1. (Transmissivity and reflectivity will depend on material properties)**
- **Incident flux (3 possible choices)**
  - **Solar calculator**
  - **Specified by the user**
  - **Isotropic flux from the environment**

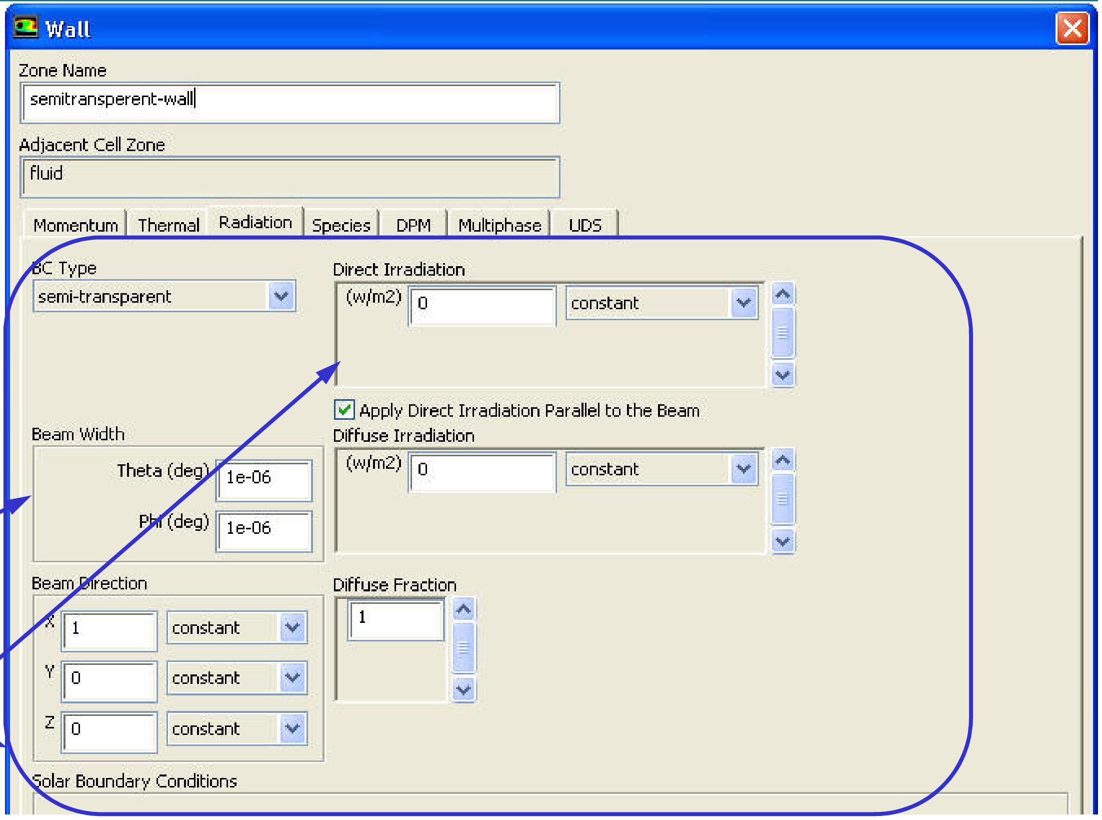
Note: Internal emissivity if appearing on the panel is not taken into account for semi-transparent walls

DO – External Semi-Transparent Walls

- **Isotropic flux from the environment (recommended)**
  - **Obtained with radiation or mixed thermal B.C.**

$$I_{\text{rad}} = \frac{\varepsilon_{\text{external}}\,\sigma T^4_{\text{ext, rad}}}{\pi}$$

  - **ε_{ext} = External emissivity from thermal BC panel**
  - **$T_{ext\ rad}$ = Radiation temperature from thermal BC panel**
- **Specified by the user**
  - **Direction**
  - **Beam width**
    - **$0 < \varphi < 360°$ and $0 < \theta < 180°$**
  - **Irradiation**
- **Note: If you forget to specify incident flux it means that the environment is at 0 K for the radiation!**



DO – Internal Semi-Transparent Walls

- **Internal wall (wall / wall shadow)**
  - **Diffuse fraction between 0 and 1**
    - **Example:**
      - **Frosted glass 1**
      - **Ideal mirror 0**
  - **Transmittivity and reflectivity will depend on material properties and in some cases (when $d_f \neq 1$)on the incident angle.**
  - **For a zero-thickness wall, absorbed energy is calculated but not dissipated (Emitted energy by the volume is not taken into account)**

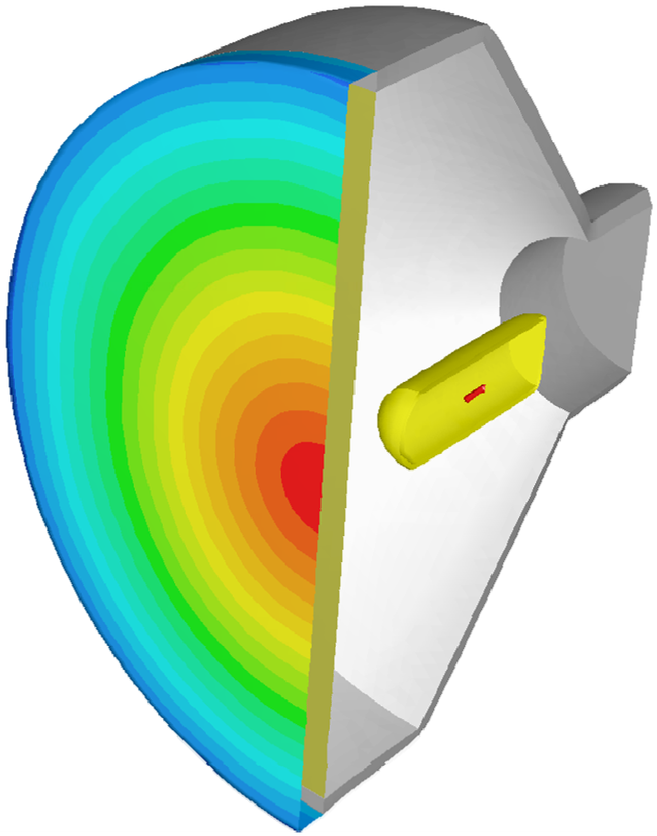
DO – UDF Macros

- **DEFINE_DOM_SPECULAR_REFLECTIVITY**
- **DEFINE_DOM_DIFFUSE_REFLECTIVITY**
  - Allows the definition of user-defined reflectity and transmittivity at a wall. (You can specify properties of the window instead of the material properties of each sheet of glass)
- **DEFINE_DOM_SOURCE**
  - Allow the modification of emission, absorption and in-scattering
- **DEFINE_SCATTERING_PHASE_FUNCTION**
  - User defined scattering phase function

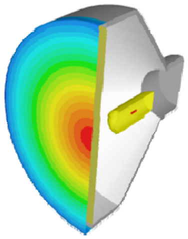
DO Example #1 – Automotive Headlight

- **Geometry and meshing**
  - **140,000 tetrahedral volume elements**

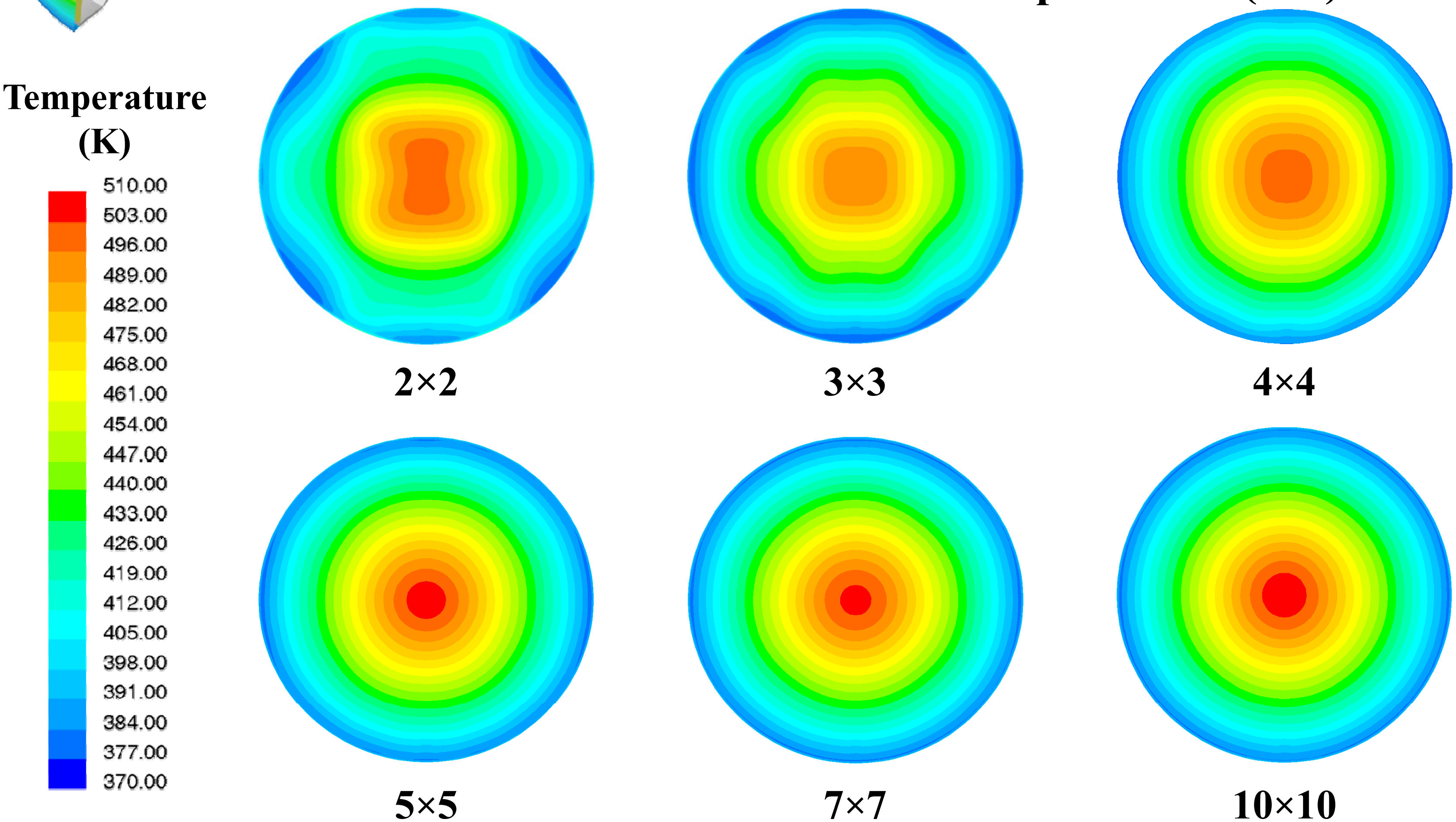
- **Radiation effects included in the DO model**
  - **Gray surfaces**
  - **Focused and diffuse**
  - **Emission**
  - **Semi-transparent wall**
  - **Symmetry**



DO Example #1 – Automotive Headlight



Influence of discretization with constant pixelation (3x3)



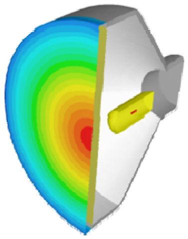
DO Example #1 – Automotive Headlight

- **Effect of pixelation on CPU load**
  - **Does not consume large amounts of memory**
  - **Calculation times:**

Pixelation	Time
1×1	1
3×3	1.22
5×5	1.49
10×10	2.85

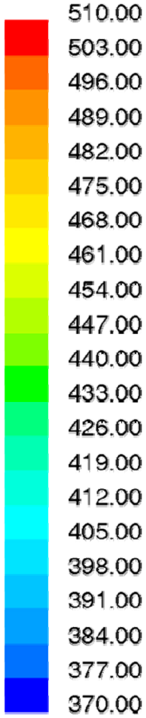
  –
  - **Not as expensive as angular discretization but effects are different.**

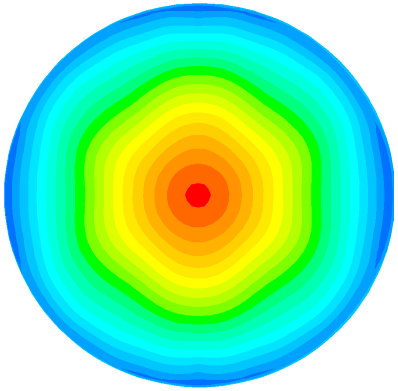
DO Example #1 – Automotive Headlight



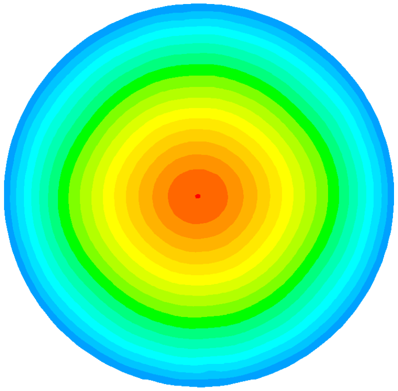
Influence of pixelation with constant discretization (5×5)

Temperature (K)

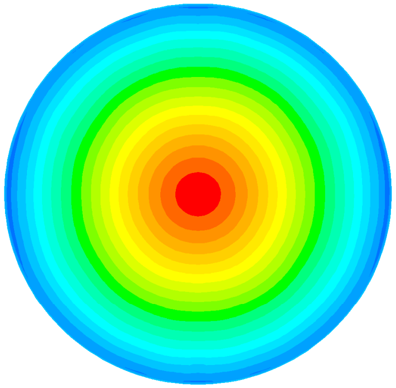




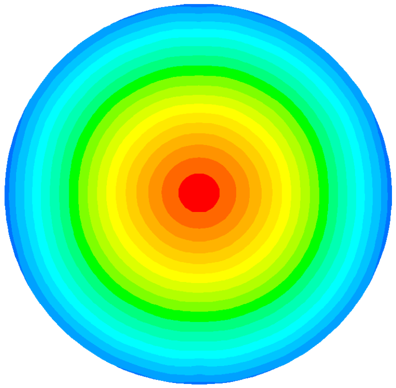
Pix. 1×1



Pix. 2×2



Pix. 3×3

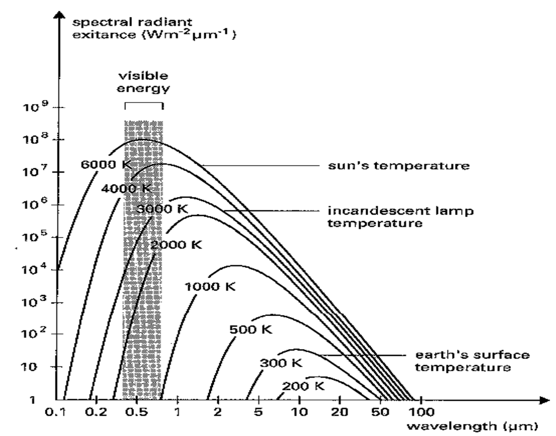


Pix. 5×5

DO – Gray Band Model

- **DOM allows to equations for a discrete number of spectral bands**
- **The absorption terms, the in-scattering and out-scattering terms depend on wavelength.**
- **Emission takes into account Planck function over the wavelength range of the band.**
- **For each band, 8 N_φ N_θ equations are solved in 3D**

$$\nabla \cdot [I_\lambda(\mathbf{r},\mathbf{s})\mathbf{s}] + (a_\lambda + \sigma_s) I_\lambda(\mathbf{r},\mathbf{s}) = a_\lambda n^2 I_{b\lambda} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I_\lambda(\mathbf{r},\mathbf{s}')\,\Phi(\mathbf{s},\mathbf{s}')\,d\Omega'$$

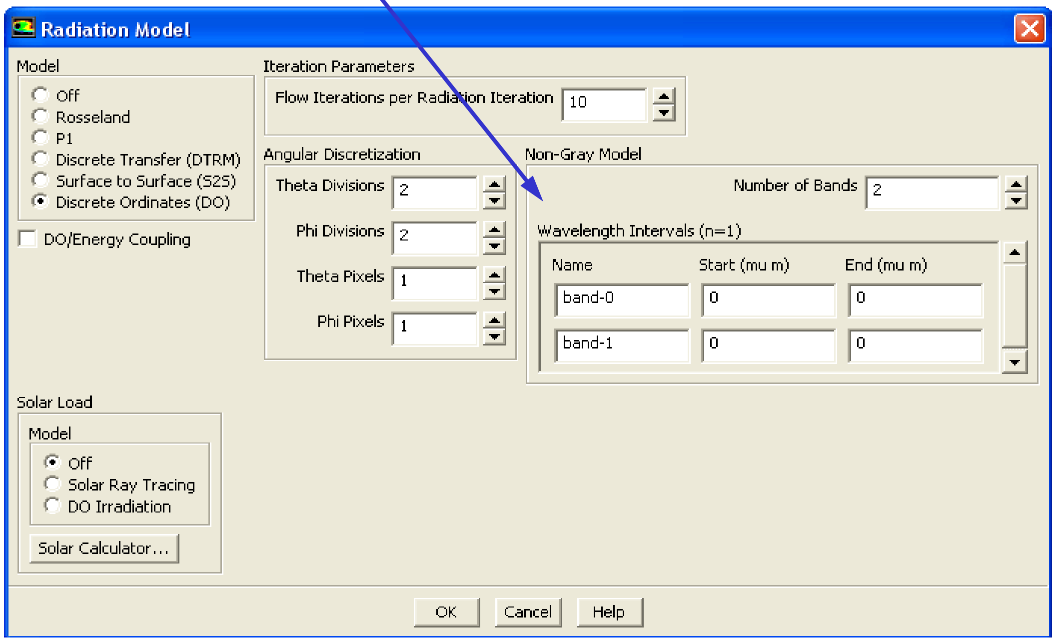


DO – Non-Gray Radiation

- **Each band is defined as an interval of wavelength given for the vacuum**
  - **You need to specify n_λ**
  - **Note that spectral properties of any materials are given for n = 1**

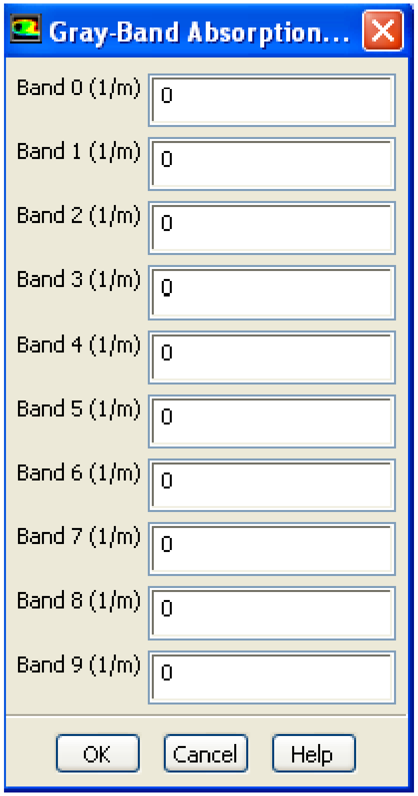
- **Be sure to cover the whole spectrum:**
  - **Limit:**

$$(n_\lambda)_{max} = \frac{5000}{T_{min}}$$



DO – Non-Gray Radiation

- **Spectral properties :**
  - **Absorption coefficient**
  - **Refractive index**



- **Boundary conditions :**
  - **Internal emissivity and incident radiation can be specified on a band by band basis**

- **Note:**
  - **For high optical thickness (higher than 5), a second-order scheme to solve discrete ordinates is recommended**

DO – Advantages and Limitations

- **Advantages**
  - Applicable to all optical thicknesses
  - Particulate and anisotropic scattering (linear, Delta-Eddington, user-defined)
  - Radiation in semi-transparent media (refraction, reflection)
  - Diffuse and specular reflection
  - Non-gray banded radiation modeling
  - Various UDFs allow customization of the model and BCs

- **Disadvantages**
  - Finite number of radiation directions causes numerical smearing
  - Computationally expensive

Radiation

- Radiation modeling theory
- **Radiation models in FLUENT**
  - Surface-to-Surface (S2S)
  - Discrete Ordinates (DO)
  - **Discrete Transfer Radiation Model (DTRM)**
  - P-1
  - Rosseland
- Selecting a radiation model
- Postprocessing
- Conclusions
- Appendix

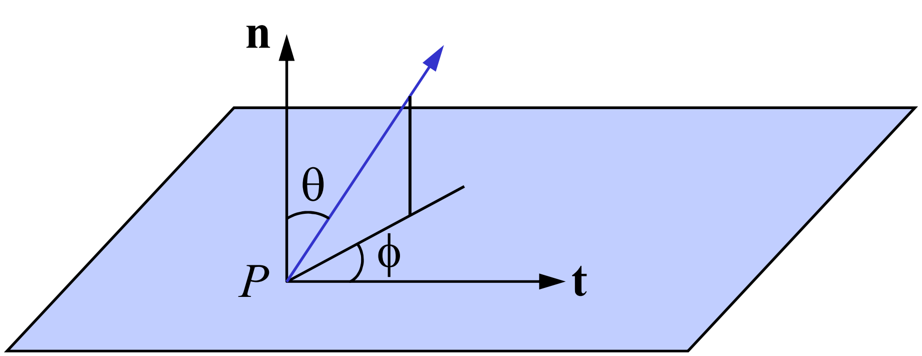
Discrete Transfer Radiation Model (DTRM)

- **In the DTRM, the radiation transfer equation is solved along straight rays:**

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

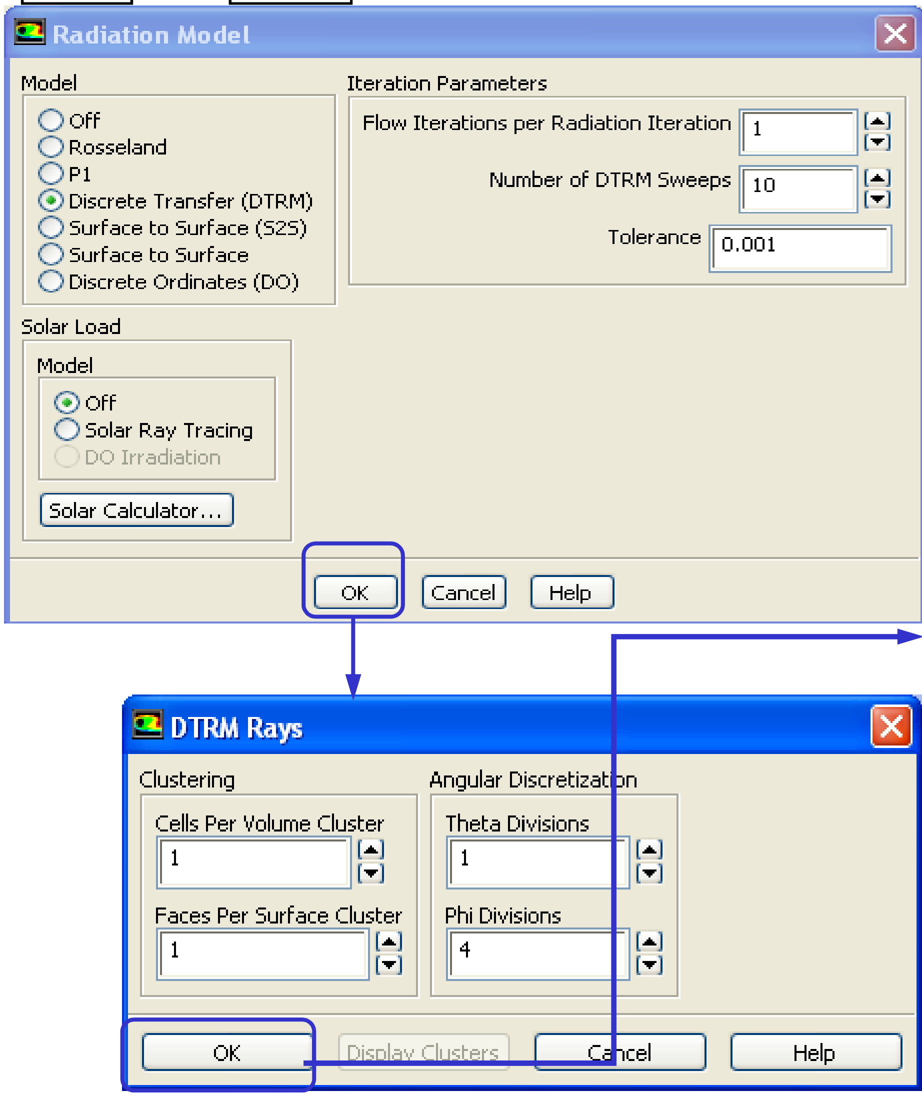
Only absorption and emission are accounted for along the ray path

- **Tracking of straight rays emitted from boundary faces**
- **Assumes that radiation over a certain range of solid angles from a boundary face can be approximated by a single ray.**
- **Prescribed azimuthal ($0 < \varphi < 2\pi$) and polar ($0 < \theta < \pi/2$) directions used to define rays**

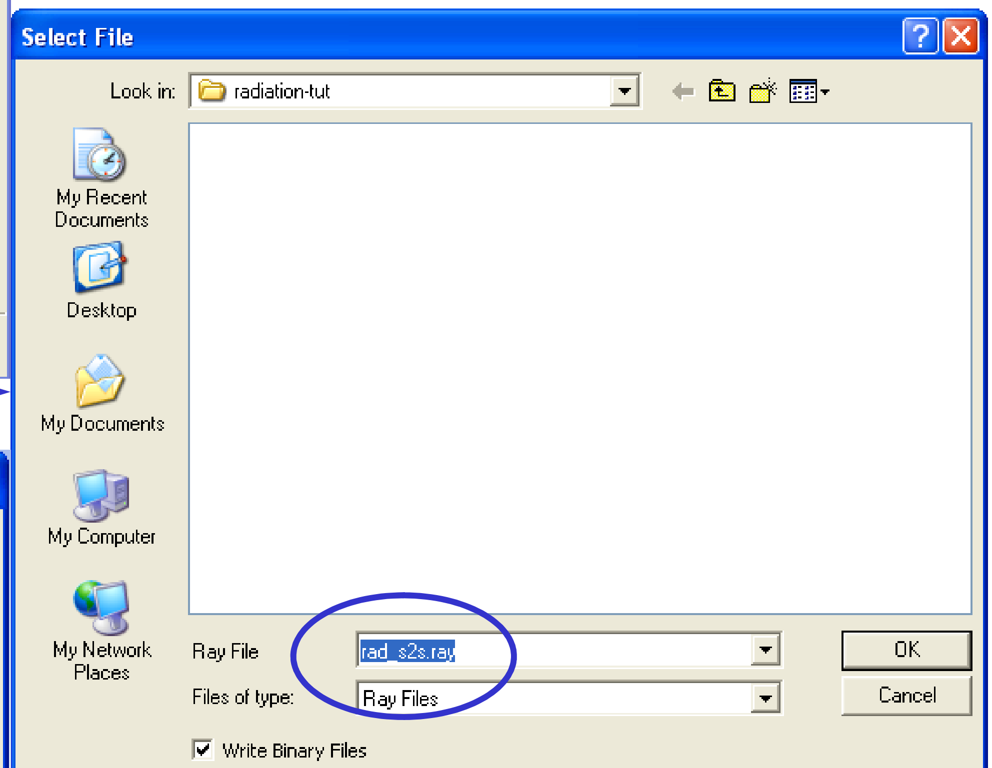


Activating the DTRM

Define → Models → Radiation…



Initial calculation of ray coefficients are saved in a **.ray** file



DTRM – Advantages and Limitations

- Advantages
  - Simple directional model (shadow effects are possible)
- Limitations
  - Cannot account for scattering
  - No particle/radiation interaction (too complex!)
  - Computationally expensive as the number of rays increases. This can be reduced by surface and volume clustering at the expense of accuracy.
  - Can only account for diffuse surfaces (not "specular" polished walls).
  - Gray gas approximation (no wavelength effects)
  - Cannot use hanging node adaption
  - Not available in parallel
  - Not conservative (difficult to verify heat balance)
  - Best with optically thin media

Radiation

- Radiation modeling theory
- **Radiation models in FLUENT**
  - Surface-to-Surface (S2S)
  - Discrete Ordinates (DO)
  - Discrete Transfer Radiation Model (DTRM)
  - **P-1**
  - Rosseland
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P-1 Model

- **The P-1 model implementation in FLUENT is a four-term truncation of the general P-*n* model, which expands the RTE into an orthogonal series of spherical harmonics.**

- **Solves a simple diffusion equation for the incident radiation (G). This value is the sum of all radiative intensity in all directions.**

$$\underbrace{\frac{\partial}{\partial x_i}\left(\Gamma \frac{\partial G}{\partial x_i}\right)}_{\text{Diffusion}} + \underbrace{4 a \sigma T^4}_{\text{Emission}} = \underbrace{a G}_{\text{Absorption}}$$

P-1 Model

- **Scattering effects can be modeled by altering the diffusivity:**

$$\Gamma = -\frac{1}{3\left(a + \sigma_s\right) - C\,\sigma_s}$$

- **C is the linear-anisotropic phase function coefficient (-1 < C < 1), which dictates the fraction of radiant energy scattered forward (positive C) or backward (negative C) to the direction of incident radiation.**

- **Radiation flux, q_i, is then**

$$q_i = -\Gamma \frac{\partial G}{\partial x_i}$$

P-1 Model – Advantages and Disadvantages

- **Advantages**
  - **Simple, single diffusion equation**
  - **Computationally cheap**
  - **Accurate for α L > 1 (coal fire)**
  - **Allows particulate (and anisotropic) scattering**
  - **Conservative**

- **Disadvantages**
  - **Participating media must be optically thick (α L > 1)**
  - **Since α ~ 1 m^{-1} for hydrocarbon combustion, use for combustor dimensions larger than 1 meter.**
  - **Loses accuracy at localized heat sources/sinks (tends to overpredict the radiative heat flux)**
  - **Assumes gray gases.**
  - **Can only account for diffuse wall surfaces (does not allow specular reflection)**

Radiation

- Radiation modeling theory
- **Radiation models in FLUENT**
  - Surface-to-Surface (S2S)
  - Discrete Ordinates (DO)
  - Discrete Transfer Radiation Model (DTRM)
  - P-1
  - **Rosseland**
- Selecting a radiation model
- Postprocessing
- Conclusions
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The Rosseland Model

- The other extreme is a very optically thick medium, (α L > 5)
- Radiative equilibrium is achieved and radiation acts purely diffusively with source terms due to emission.
  - Radiation intensity is the black body intensity at the gas temperature

$$G = 4 n^2 \sigma T^4$$

  - The radiative heat flux diffuses due to high optical thickness

$$q_r = -\Gamma \frac{\partial G}{\partial x_i}$$

  - Combining these equations gives a simple equation for the local radiative heat flux related to local temperature

$$q_r = -16 n^2 \sigma \Gamma T^3 \frac{\partial T}{\partial x_i}$$

- Example of an optically thick medium is melted glass

Advantages/Disadvantages of the Rosseland Model

- **Advantages**
  - Computationally inexpensive
  - No transport equations!
- **Disadvantages**
  - Only valid for media with very large optical thickness
  - Not available in the density-based solvers

Radiation

- Radiation modeling theory
- Radiation models in FLUENT
  - Surface-to-Surface (S2S)
  - Discrete Ordinates (DO)
  - Discrete Transfer Radiation Model (DTRM)
  - P-1
  - Rosseland
- **Selecting a radiation model**
- Postprocessing
- Conclusions
- Appendix

The Concept of Optical Thickness

- **An important dimensionless number in radiation problems the optical thickness.**
  - **Optical thickness indicates how strongly radiation is absorbed (and scattered)**
  - **Should be used in determining which model(s) are appropriate for a given case.**

$$\text{Optical thickness} \equiv (\alpha + \sigma_s)\, L$$

α = absorption coefficient

σ_s = scattering coefficient (often = 0)

L = mean beam length

- **A simple measure of optical thickness is (α L)**
  - **α = absorption coefficient (m^{-1})**
  - **L = mean beam length (m) (typical distance between two opposing walls)**

Choosing a Radiation Model

Available Model	Optical Thickness
Surface to surface model (S2S)	0
Solar load model	0 (except window panes)
Rosseland	> 3
P-1	> 1
Discrete ordinates method (DOM)	All
Discrete Transfer Radiation Model (DTRM)	All

Note: S2S and DOM are the most commonly-used models

Which Model is Best for My Application?

Application	Model/Method
Underhood	S2S, DO
Headlamp	DO (non-gray)
Combustion in large boilers	DO, P1 (WSGGM)
Combustion	DO, DTRM (WSGGM)
Glass applications	Rosseland, P1, DO (non-gray)
Greenhouse effect	DO
UV Disinfection (water treatment)	DO, P1 (UDF)
HVAC	Solar load model (UDF), DO, S2S

Selecting a Radiation Model

- **Optical thickness is the key parameter but some other parameters should also be considered**
  - **Model compatibility**
    - **Adaption impossible when using S2S and DTRM**
    - **DTRM is not available in parallel.**
  - **Time for view factor calculations (S2S only)**
  - **Memory (DO model)**

Discretization	Memory
2×2	1.0 → ≈ 1.8 kB/cell
3×3	1.25
5×5	2.06
7×7	3.27
10×10	5.80

Radiation

Postprocessing

- **Radiation contours**
  - **Incident radiation**
  - **Radiation temperature**
  - **Absorption coefficient**
- **Wall flux contours**
  - **Radiation Heat Flux**
  - **Surface Incident Radiation (P1,DOM)**
  - **Transmitted Radiation (for each band) (DOM)**
  - **Reflected Radiation (for each band) (DOM)**
  - **Absorbed Radiation (for each band) (DOM)**

- **With the TUI command**

```
solve/set/expert/keep-temporary-memory-from-being-freed? Yes
```

one can have access at each radiant intensity for each discrete direction (only available with DO model)

Heat Balance: Report→Fluxes

- **Total Heat Transfer Rate: convective and radiative flux are taken into account**
  - **Net heat balance should be 0 once converged or opposite to all the energy sources (UDF or constant sources, DPM)**

- **Radiation Heat Transfer Rate: Only radiative net flux is taken into account;**
  - **The sum of this flux is generally different from 0. It can represent the amount of energy that is absorbed by the media.**

Radiation

- Radiation modeling theory
- Radiation models in FLUENT
  – Surface-to-Surface (S2S)
  – Discrete Ordinates (DO)
  – Discrete Transfer Radiation Model (DTRM)
  – P-1
  – Rosseland
- Selecting a radiation model
- Postprocessing
- **Conclusions**
- Appendix

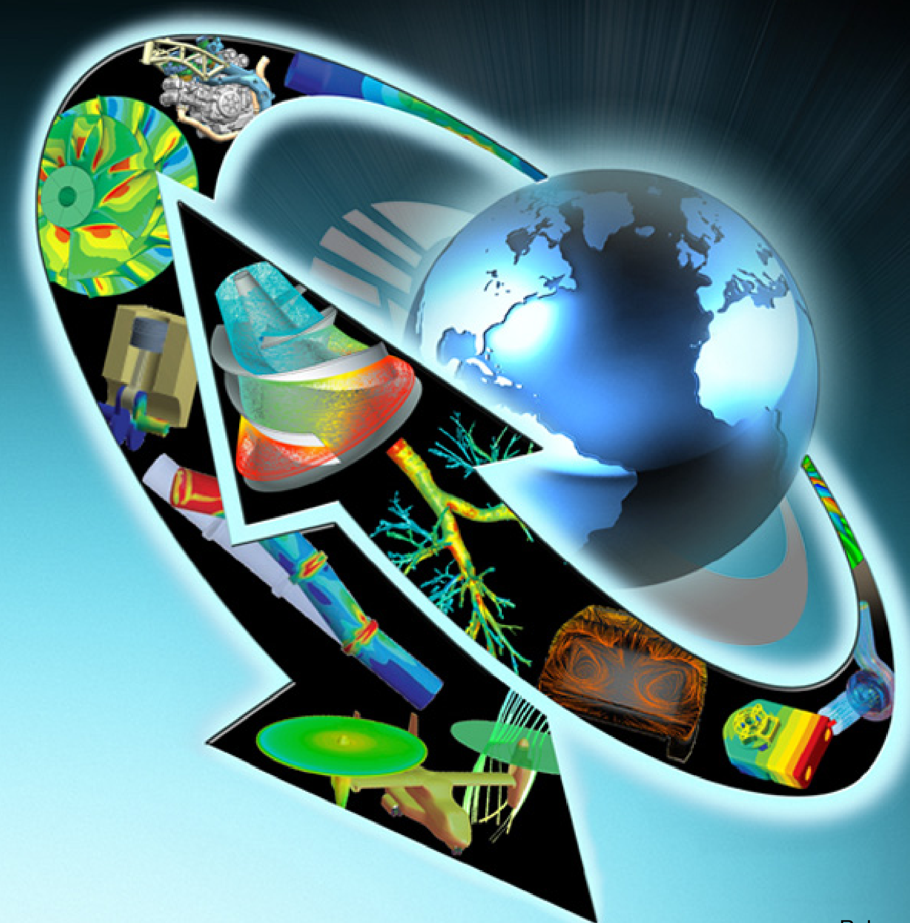
Conclusions

- **Radiation can be expensive!**
- **Check order of magnitude of radiative flux compared to convective flux.**
- **Choose the most appropriate method to solve your problem.**
- **Choose resolution parameters that fits with your computers.**

References

- S. Braun – UGM2003 Fluent Deutschland: “Radiation calculation in practice”
- H. Ghazialam- UGM2002 US: “Underhood flow and thermal analysis”
- FLUENT 6 user‘s guide (available on www.fluentusers.com)
- FIDAP Theory Manual (available on www.fluentusers.com)
- R. Siegel & J. Howel, Thermal radiation heat transfer 4th edition
- F. P. Incropera & D. P. DeWitt, Mass Fundamental of Heat and Transfer 4th edition

Appendix



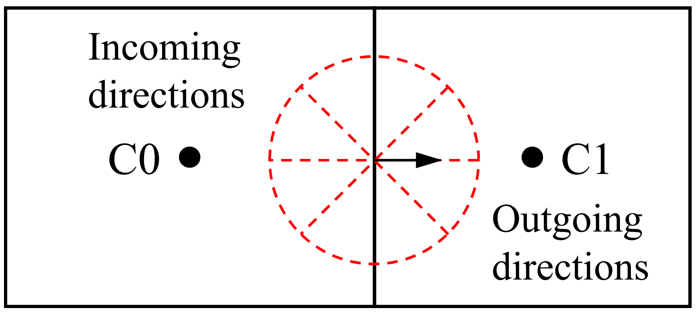
Lecture 5

Radiation Heat Transfer

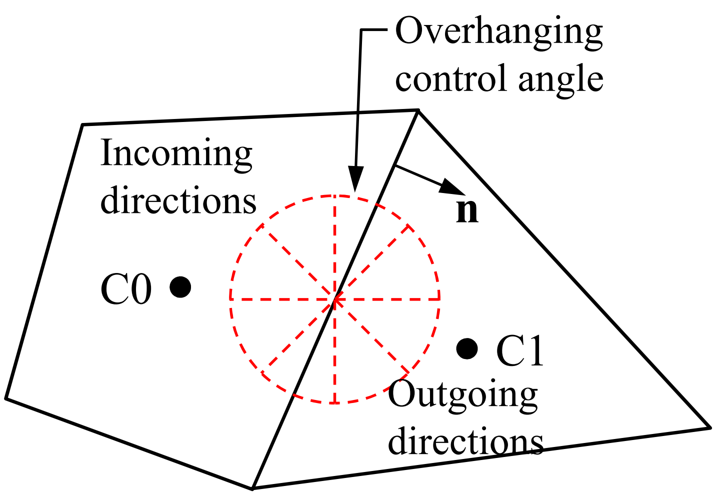
Release 13.0
December 2010

DO – Control Angle Overhang

- **Mesh and control angles may or may not be coincident.**



Face with no control angle overhang

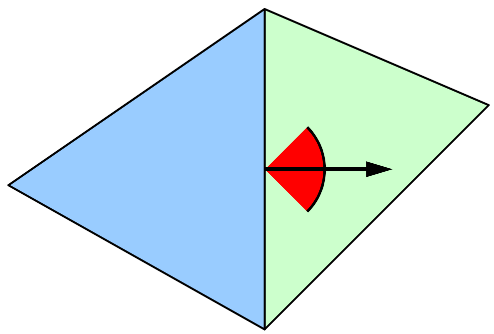


Face with no control angle overhang:

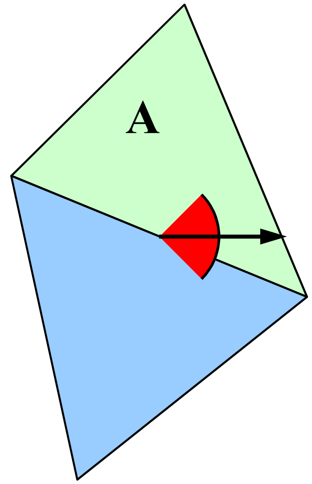
Some control angles are crossed by an elementary face

DO – Pixelation

- **Because each ordinate represents the radiation due to a complete solid control angle, some errors may occur when a ray passes from one cell to the next:**



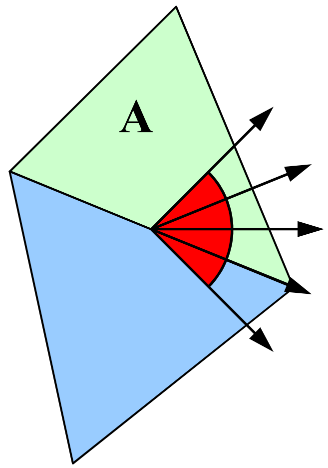
All ray's energy passes into the same cell



Only part of ray's energy passes through the face into cell A.

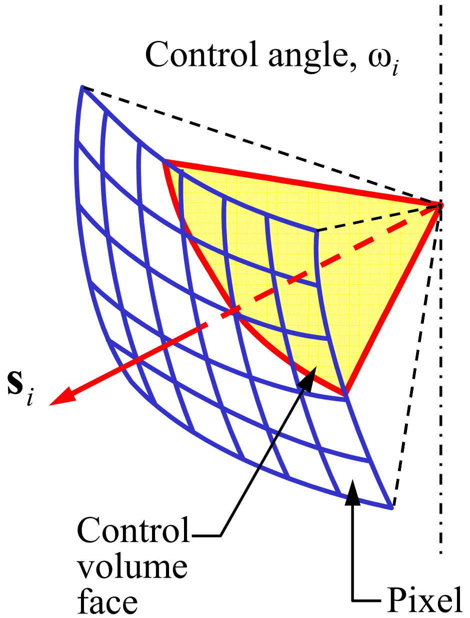
DO – Pixelation

- **The solid angle of the beam is split into smaller pixels that are individually tested to see which part of radiative intensity exits that face.**



Control angle split into pixels

- **Recommendation: (3×3)**
- **Important when one of the boundary is**
  - **Symmetry**
  - **Periodic**
  - **Specular or semi-transparent**



ANSYS

Customer Training Material

Solution Strategies

Heat Transfer Modeling using ANSYS FLUENT

Release 13.0
December 2010

Radiation / Convection Coupling

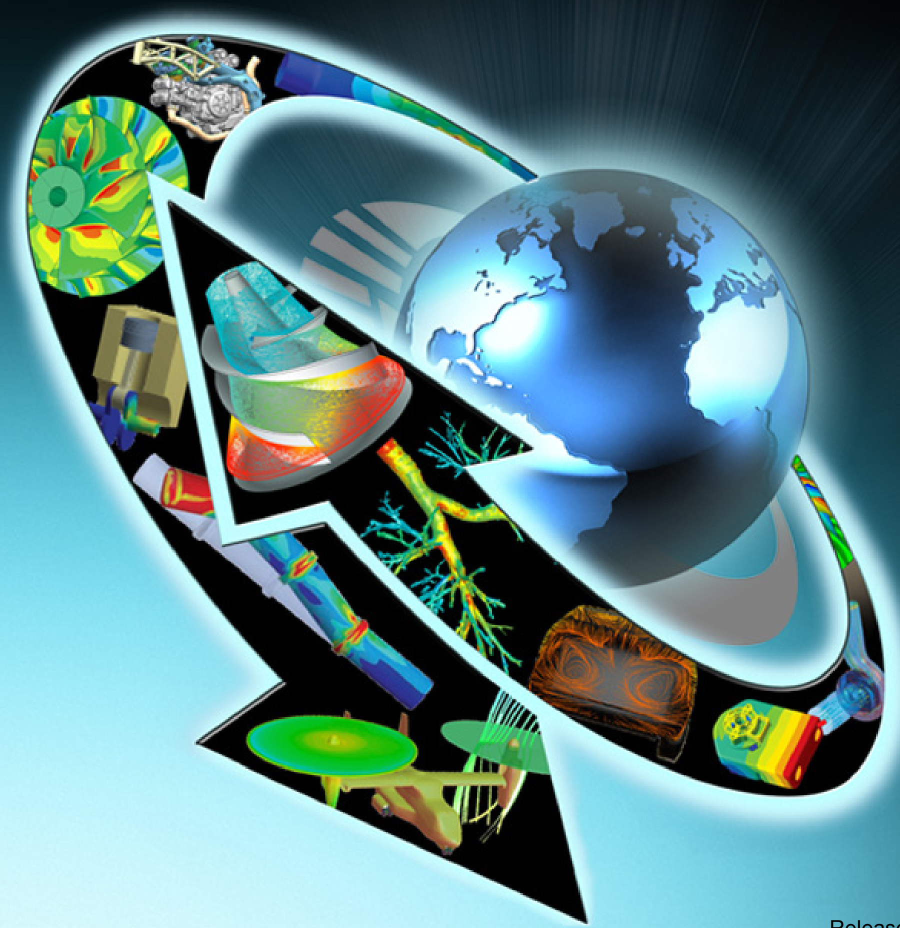
- **Convection-dominated flow**
  - **Calculate flow and energy until nearly converged.**
  - **Turn on radiation and calculate radiation and energy for > 20 iterations**
  - **Calculate flow, energy and radiation together until convergence**
    - **DO model only – Perform a radiation iteration every 3-10 flow iterations**

- **Radiation-dominated flow**
  - **Calculate radiation and energy**
    - **Radiation *every* flow iteration for about 50 iterations**
  - **Calculate flow and energy until nearly converged**
    - **DO model only – Perform a radiation iteration every 3-10 flow iterations**
  - **Calculate flow, energy and radiation until convergence**

Customer Training Material

Case Study #1

Radiation Heat Transfer

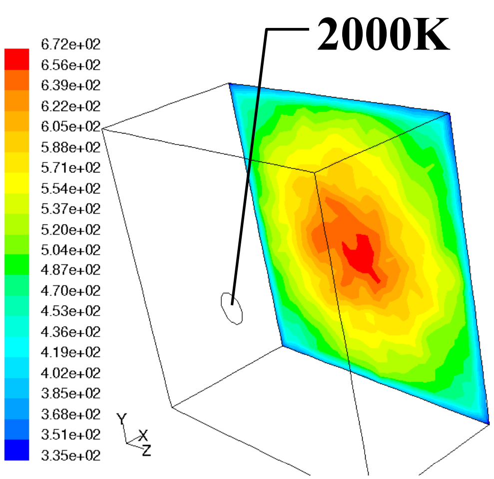


Heat Transfer Modeling using ANSYS FLUENT

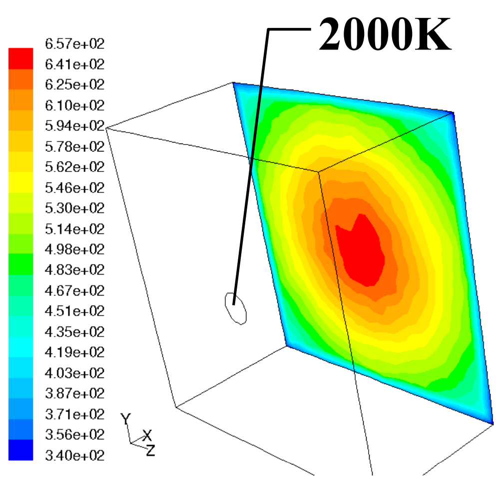
Comparison of DO with S2S

Localized Heat Source

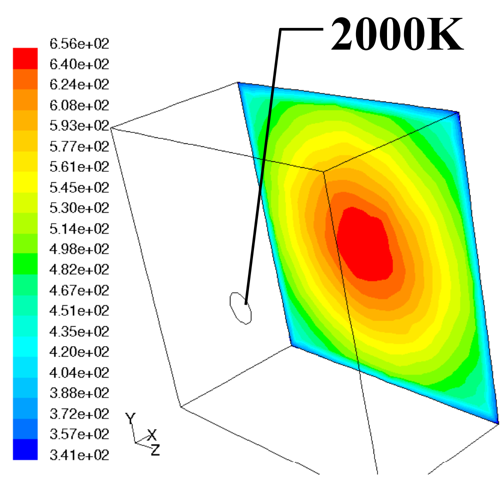
- **Localized heat source (S2S) :**



Resolution = 20



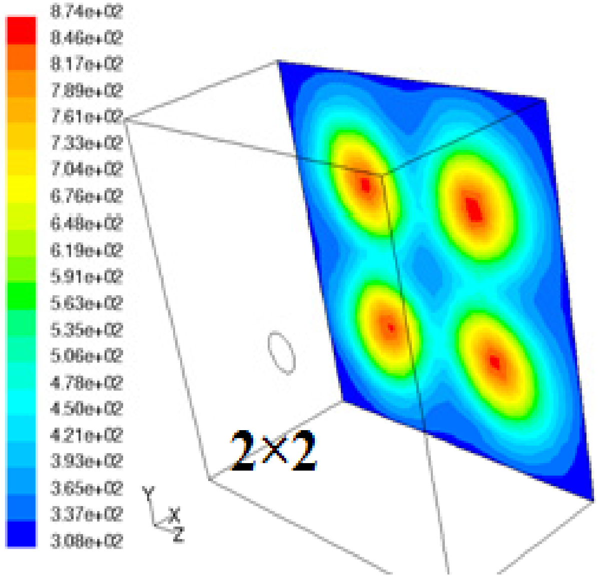
Resolution = 40

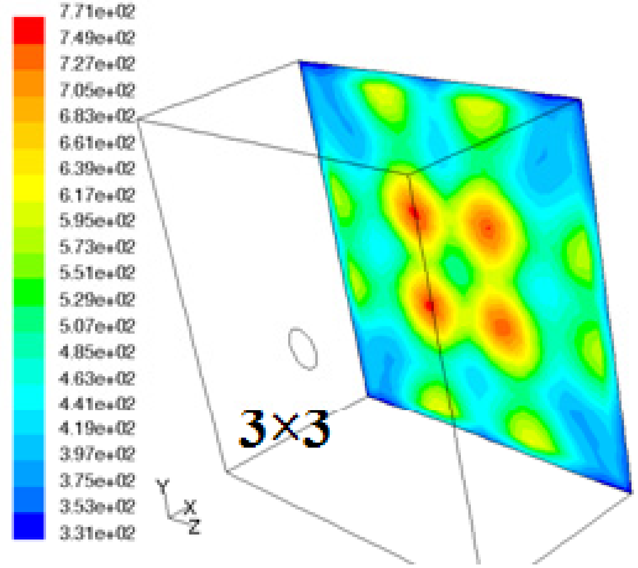


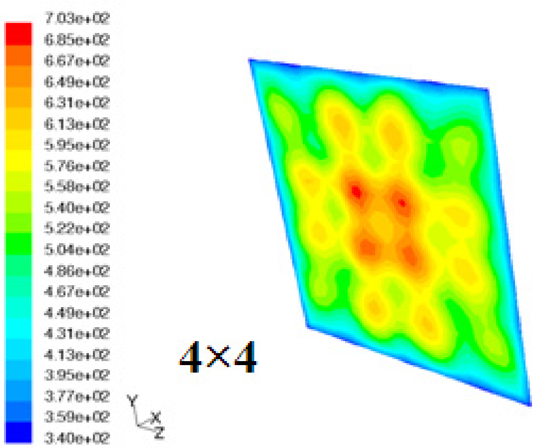
Resolution = 60

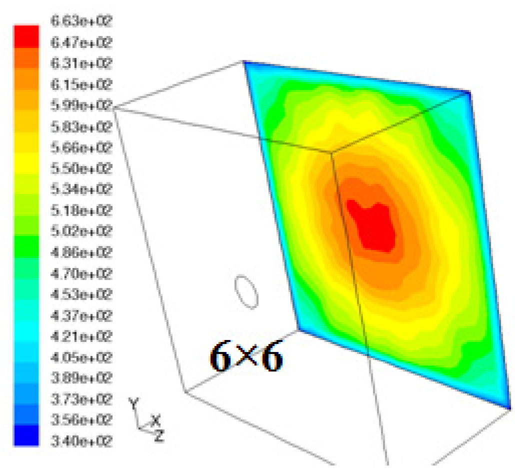
Comparison of DO with S2S

Localized Heat Source







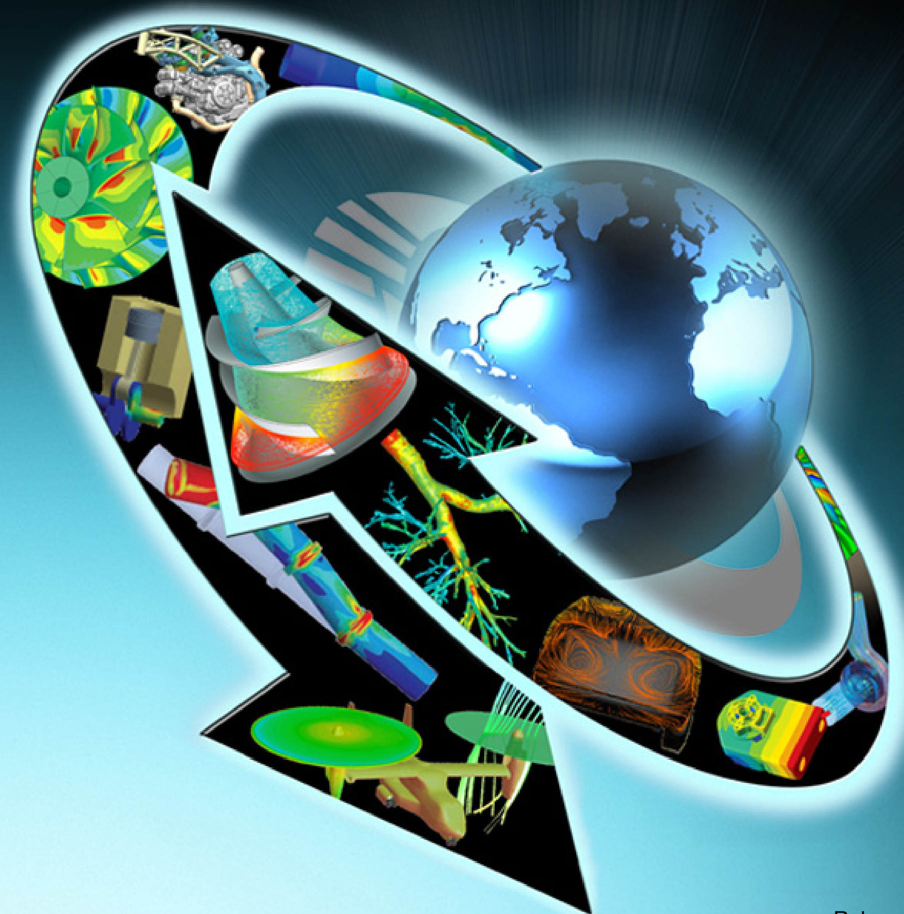


Note: result could be slightly different if one rotates the domain by 90° along y axis.

Customer Training Material

Case Study #2

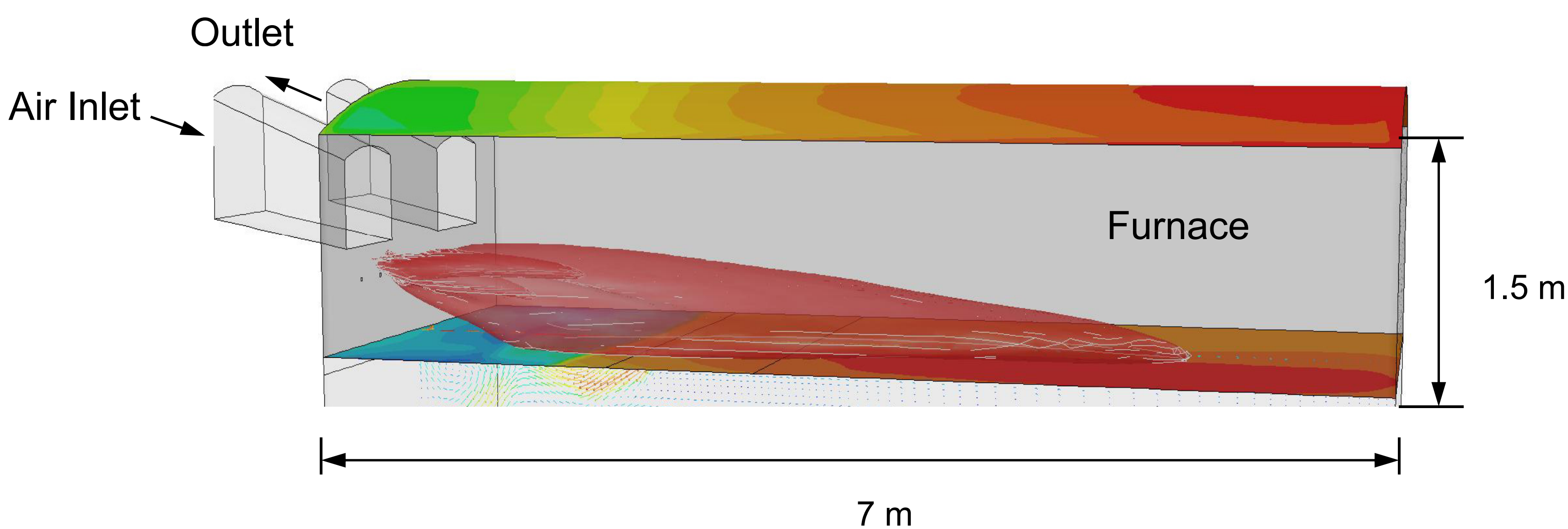
Radiation Heat Transfer



Heat Transfer Modeling using ANSYS FLUENT

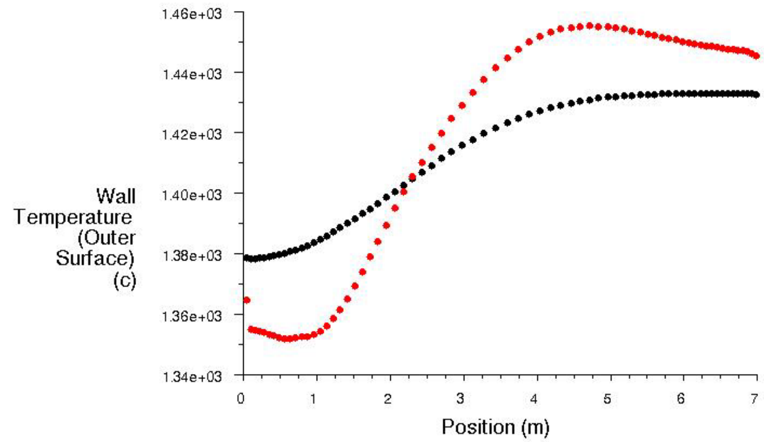
Model Setup

- **Combustion model – Non-premixed (equilibrium PDF).**
- **Radiation material properties**
  - **Absorption properties of the gas are computed with domain-based WSGGM (the recommended option)**
  - **Average resulting absorption coefficient between 0.1 and 0.2 m^{-1}**
  - **Optical thickness between 0.2 and 0.3 m.**
- **Thermal boundary conditions**
  - **Temperature profile prescribed on the bottom surface**
  - **Convection boundary condition on the top and side walls**

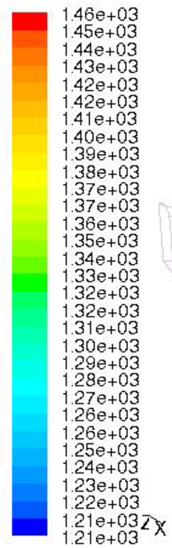


Results

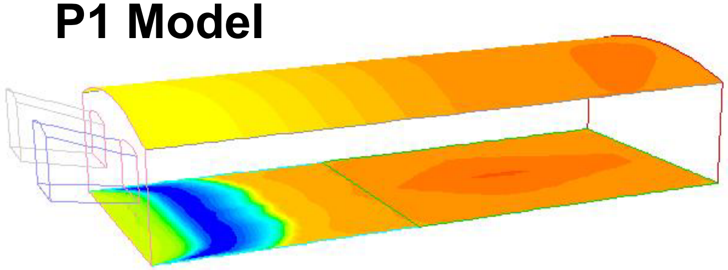
- **Comparison of P1 vs. DO**
  - **In both cases, the same combustion model is used.**
  - **Same temperature profile on the bottom wall is used.**
  - **Crown temperature is the variable of interest.**



Crown Temperature Profile (°C)

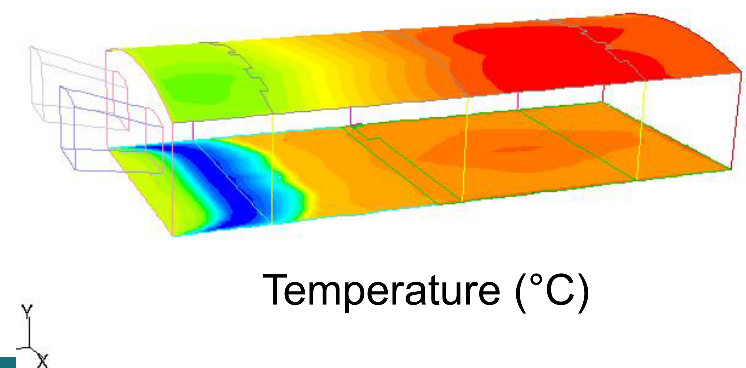


P1 Model



Temperature (°C)

DO Model



Temperature (°C)

Glass Furnace Case Study

- **Other results of interest: Transferred heat flux to the bottom wall (glass tank)**

Model	Heat Flux to Bottom Wall (kW)	CPU Time Required (sec/iteration)
DO	879.7	10
P1	769.4	2.3

Burner power = 1.5 MW.

Most of the energy is radiative (~90%)

- **Conclusion**
  - **Since the optical thickness is less than 1, P1 smoothes the temperature gradients and thus calculates a lower heat flux to the glass tank.**

- **Note on DO calculation**
  - **Calculation was first performed with 2×2 discretization and later increased to 5×5.**
  - **When the angular discretization is changed, the DO equations can only be solved before recoupling the momentum and energy equations.**
  - **Momentum-radiation coupling was performed at each iteration.**