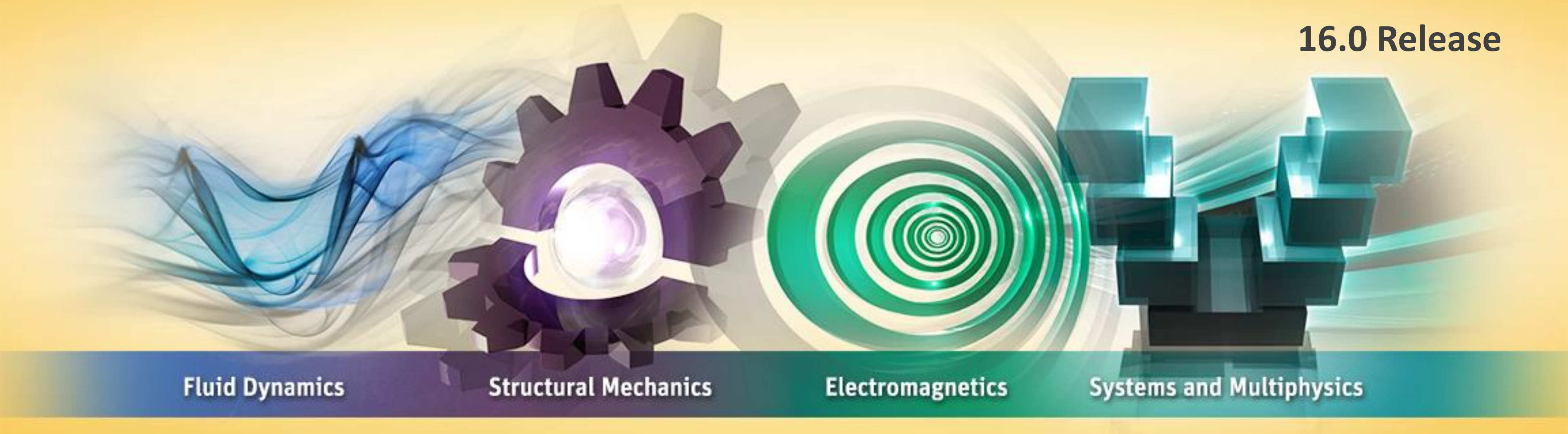
Lecture 9:
Heat Transfer

16.0 Release



Introduction to ANSYS CFX

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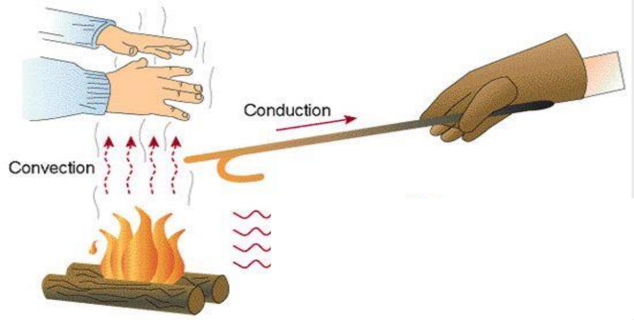
Introduction

- **Lecture Theme:**
  - **Heat transfer has broad applications across all industries. All modes of heat transfer (conduction, convection – forced and natural, radiation, phase change) can be modeled.**
- **Learning Aims:**
  - **You will be familiar with CFX's heat transfer modeling capabilities and be able to set up and solve problems involving all modes of heat transfer**

Mechanisms

- Convection
  - Heat transfer due to the bulk movement of a fluid
  - Forced: flow is induced by some external means
  - Natural or Free: fluid moves due to buoyancy effects
  - Boiling: phase change (not covered in this course)

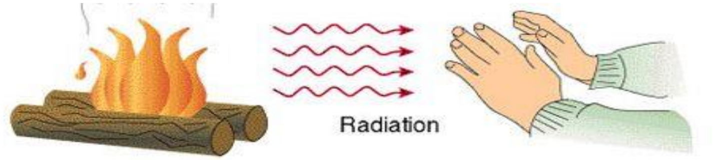


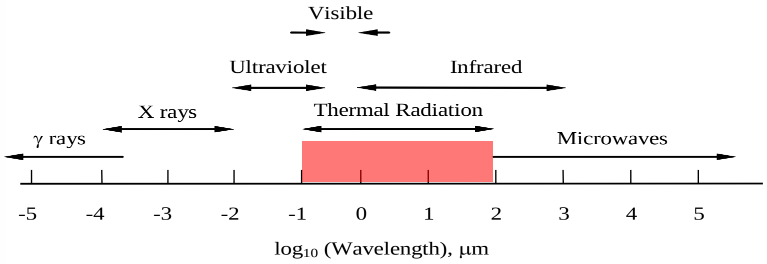
- Conduction
  - Heat transfer in a fluid or solid due to differences in temperature
  - Conduction is described by Fourier's law:
    - heat flux is directly proportional to the negative temperature gradient

$$q_{\text{conduction}} = -\overset{\text{Thermal conductivity}}{k} \, \nabla T$$

Mechanisms

- Radiation
  - Transfer of thermal energy by electromagnetic waves from 0.1 µm (ultraviolet) to 100 µm (mid-infrared)
  - Radiation intensity is directionally and spatially dependent
- Viscous Dissipation
  - Energy source due to viscous heating
  - Important when viscous shear in fluid is large (e.g., lubrication) and/or in high-velocity, compressible flows



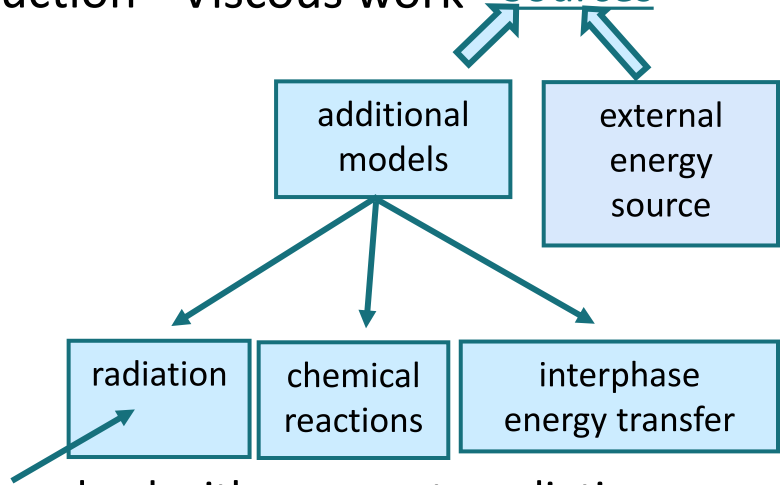


Governing Equation : Fluid domain

$$\underbrace{\frac{\partial(\rho h_{tot})}{\partial t} - \frac{\partial p}{\partial t}}_{\text{Transient}} + \underbrace{\nabla\cdot(\rho U\, h_{tot})}_{\text{Advection}} = \underbrace{\nabla\cdot(\lambda\nabla T)}_{\text{Conduction}} + \underbrace{\nabla\cdot(U\cdot\tau)}_{\text{Viscous work}} + \underbrace{S_E}_{\text{Sources}}$$

h_{tot}, total enthalpy, is related to static enthalpy, *h*, as follows:

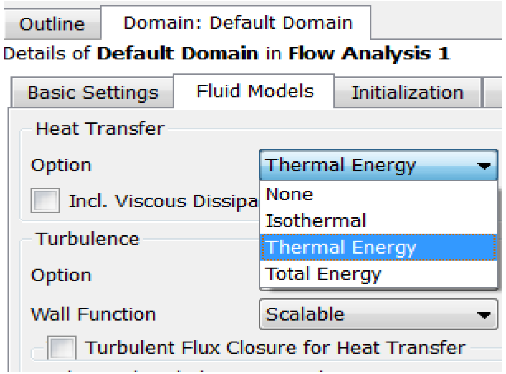
$$h_{tot} = h + \frac{1}{2}U^2$$



Radiation is solved with a separate radiative transport equation

Heat Transfer Models: Fluid Domains

- Heat Transfer option
  - None:
    - Energy Transport not solved
  - Isothermal:
    - Energy Transport not solved, temperature is set for the evaluation of fluid properties
  - Thermal Energy:
    - Energy Transport is solved; kinetic energy effects neglected
    - For low speed flow
  - Total Energy:
    - Transport of enthalpy and kinetic energy effects
    - For Mach number > 0.3 or compressibility effects,
    - For low speed liquid flow when the specific heat is not constant



Details of **Default Domain** in **Flow Analysis 1**

Heat Transfer

Option: Thermal Energy

☐ Incl. Viscous Dissipa

Turbulence

Option

Wall Function: Scalable

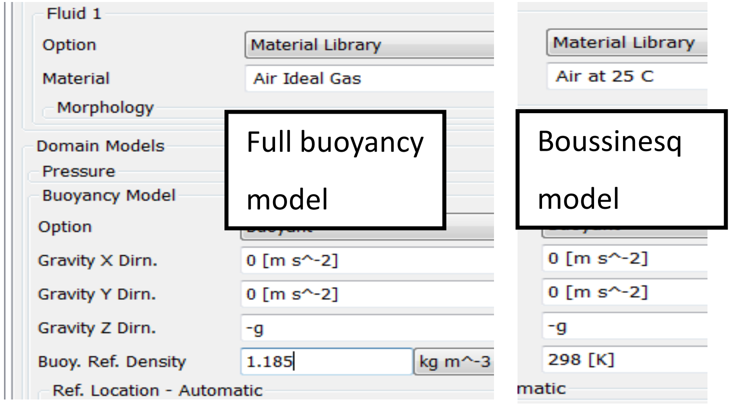
☐ Turbulent Flux Closure for Heat Transfer

Heat Transfer Models: Fluid Domains

- If natural convection is important, then switch on the Buoyancy Model
  - For varying density full buoyancy model used
  - For constant density Boussinesq model used
- Thermal Radiation model
  - Should be accounted for when

$$Q_{rad} = \sigma.\left(T_{\max}^{4} - T_{\min}^{4}\right) \geq Q_{conv} = h.\left(T_{wall} - T_{free}\right)$$

- Several radiation models are available which provide approximate solutions to the RTE (more information in appendix)

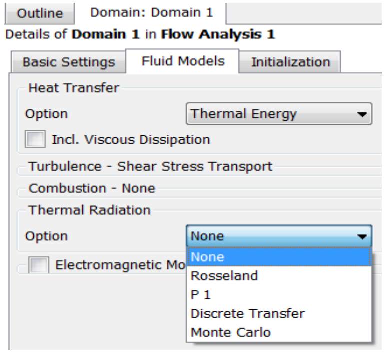


Fluid 1
Option: Material Library
Material: Air Ideal Gas
Morphology
Domain Models
Pressure
Buoyancy Model
Option
Gravity X Dirn.: 0 [m s^-2]
Gravity Y Dirn.: 0 [m s^-2]
Gravity Z Dirn.: -g
Buoy. Ref. Density: 1.185 kg m^-3
Ref. Location - Automatic

Full buoyancy model

Material Library
Air at 25 C
0 [m s^-2]
0 [m s^-2]
-g
298 [K]
matic

Boussinesq model



Details of **Domain 1** in **Flow Analysis 1**

Heat Transfer
Option: Thermal Energy
☐ Incl. Viscous Dissipation
Turbulence - Shear Stress Transport
Combustion - None
Thermal Radiation
Option: None
☐ Electromagnetic Mo

Governing Equation : Solid domains

- **Heat transfer in a solid domain is modeled using the following conduction equation:**

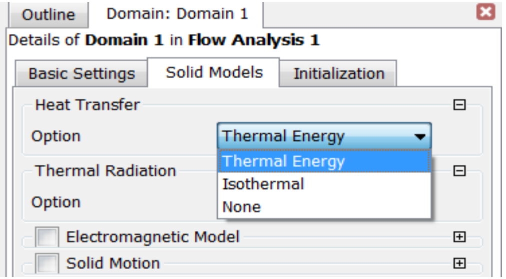
$$\underbrace{\frac{\partial(\rho h)}{\partial t}}_{\text{Transient}} + \underbrace{\nabla\cdot(\rho U_s h)}_{\text{Solid motion}} = \underbrace{\nabla\cdot(\lambda\nabla T)}_{\text{Conduction}} + \underbrace{S_E}_{\text{Source}}$$

- **h is the sensible enthalpy :**

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

Heat Transfer Models: Solid Domains

- **For conduction set Heat Transfer option to Thermal Energy**
- **Thermal radiation in solids**
  - **Required only for transparent or semi-transparent materials, e.g. glass; no radiation in opaque solids**
  - **Monte Carlo model only**

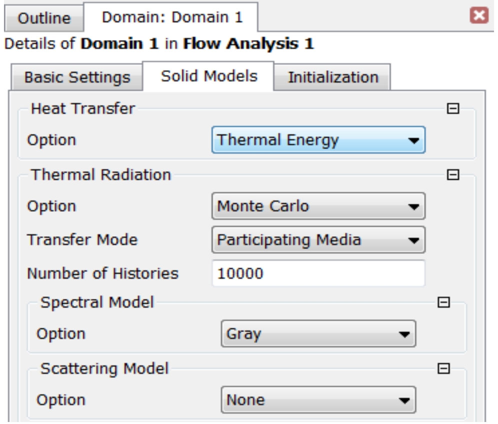


Details of **Domain 1** in **Flow Analysis 1**

Heat Transfer
Option: Thermal Energy

Thermal Radiation
Option

☐ Electromagnetic Model
☐ Solid Motion



Details of **Domain 1** in **Flow Analysis 1**

Heat Transfer
Option: Thermal Energy

Thermal Radiation
Option: Monte Carlo
Transfer Mode: Participating Media
Number of Histories: 10000

Spectral Model
Option: Gray

Scattering Model
Option: None

Thermal Wall Boundary Condition

- Thermal boundary conditions come in three types, all available in ANSYS CFX:
  - Neumann
  - Robin/Fourier
  - Dirichlet
- They represent heat transfer phenomena outside the domain

Neumann Condition

(Specified Flux)

q ($W.m^{-2}$)

Dirichlet Condition

(Specified Temperature)

T (K)

Robin/Fourier Condition

(Specified HTC)

h_{conv} ($W.m^{-2}.K^{-1}$); $q = h_{conv}.(T_{amb}-T_{body})$

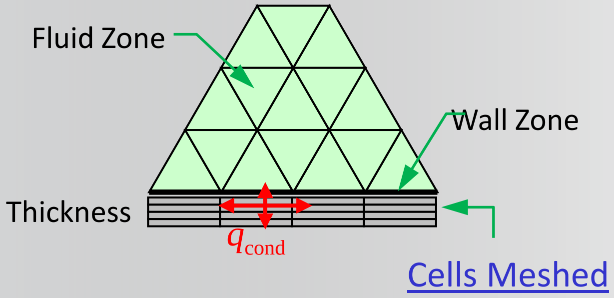
Conjugate Heat Transfer (CHT) - Domain Interfaces

- GGI connection is only option for Fluid-Solid and Solid-Solid interfaces because…
  - GGI interface
    - No discontinuity in values of temperature across the interface
    - CFX Solver calculates a "surface temperature" based on a flux-conservation equation
  - 1:1 interface
    - May result in temperature discontinuity at the interface
- Radiation conditions are set on the side in which radiation is modelled, e.g. the fluid side of a fluid/solid interface

Conjugate Heat Transfer – Modelling Walls

Wall thickness meshed:

- Fourier's Law Solved in 3D

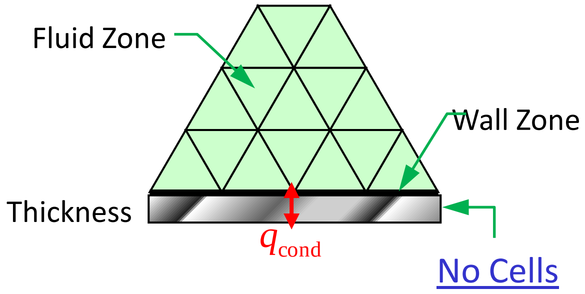


- Energy equation solved in solid
- Accurate approach → requires more meshing & computational effort

Wall thickness NOT meshed (thin wall):

- 1-D Fourier's Law through Wall

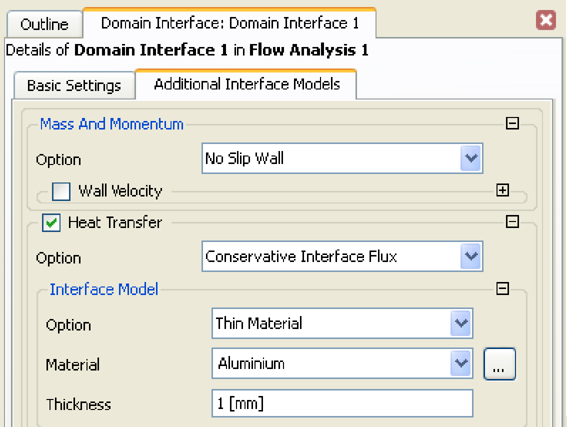
Thermal Resistance



- Artificially models conduction across wall thickness
- Limitation: conduction is assumed to be normal to the wall

Conjugate Heat Transfer – Thin walls

- **Set-up**
  - Create a Fluid-Fluid Domain Interface
  - On Additional Interface Models tab set Mass and Momentum = No Slip Wall
  - Enable Heat Transfer toggle and pick:
    - Thin Material and specify a Material & Thickness or Thermal Contact Resistance
    - Note : Other domain interface types (Fluid-Solid etc.) can use these options to represent coatings etc.



Details of **Domain Interface 1** in **Flow Analysis 1**

Mass And Momentum

Option: No Slip Wall

☐ Wall Velocity

☑ Heat Transfer

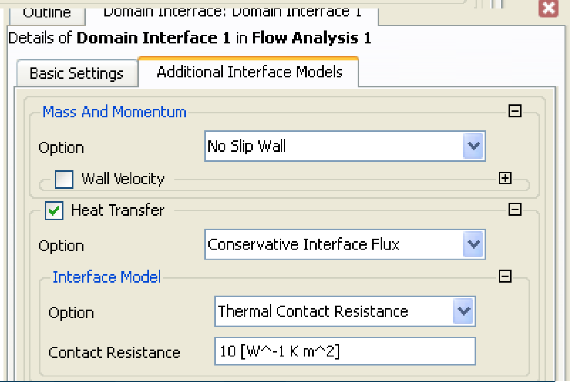
Option: Conservative Interface Flux

Interface Model

Option: Thin Material

Material: Aluminium

Thickness: 1 [mm]



Details of **Domain Interface 1** in **Flow Analysis 1**

Mass And Momentum

Option: No Slip Wall

☐ Wall Velocity

☑ Heat Transfer

Option: Conservative Interface Flux

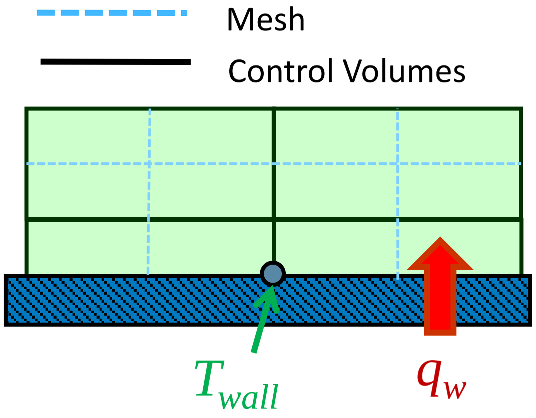
Interface Model

Option: Thermal Contact Resistance

Contact Resistance: 10 [W^-1 K m^2]

Post-Processing Heat Transfer

- **Temperature:**
  - **Local fluid temperature, plotted on a wall it is the temperature at the wall, T_{wall}**
- **Wall Adjacent Temperature:**
  - **Average temperature in control volume next to wall**
- **Wall Heat Transfer Coefficient, h_c:**
  - **Based on T_{wall} and the Wall Adjacent Temperature by default**
  - **To base it on some far-field value instead of the Wall Adjacent Temperature, use the Expert Parameter “tbulk for htc”**
- **Wall Heat Flux, q_w:**
  - **Total heat flux into the domain by all modes**
  - **Available on all boundaries**



$$q_w = h_c (T_{wall} - T_{ref})$$

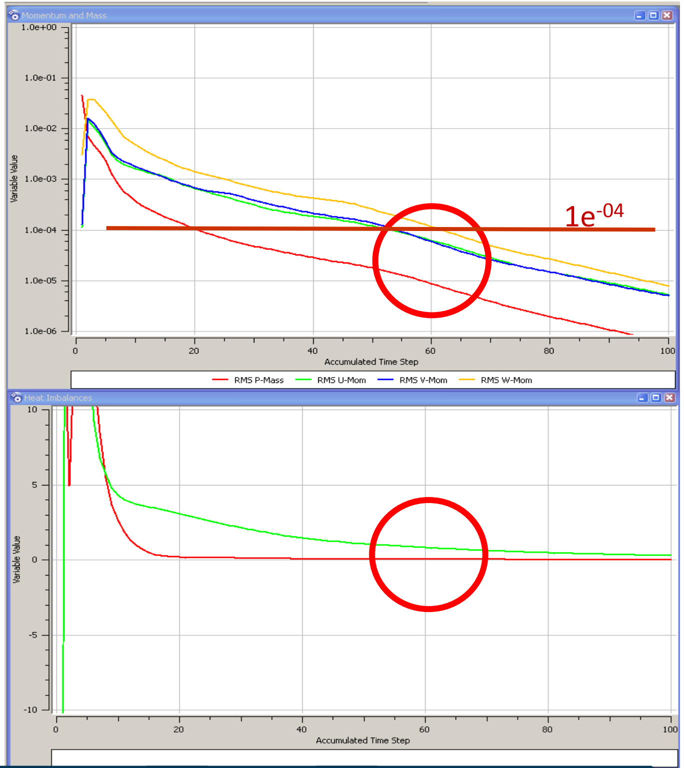
Where T_{ref} is the *Wall Adjacent Temperature* or the *tbulk for htc* temperature if specified

Post-Processing Heat Transfer

- **Heat Flux:**
  - Total convective and radiative heat flux into the domain
  - Available on all boundaries
  - On flow boundaries, it represents the energy carried with the fluid relative to its Reference Temperature
- **Wall Radiative Heat Flux:**
  - Net radiative energy leaving the boundary
  - Wall Convective Heat Flux + Wall Radiative Heat Flux = Wall Heat Flux
  - Only applicable when radiation is modeled
- **Wall Irradiation Flux:**
  - Incoming radiative flux
  - Only applicable when radiation is modeled

Solution Convergence

- Allow sufficient solution time
  - Heat imbalances in all domains have to approach zero
- Monitor
  - Create Solver Monitors showing IMBALANCE levels for fluid and solid domains
  - View the imbalance information printed at the end of the solver output file
  - Use a Conservation Target when defining Solver Control in CFX-Pre



Summary

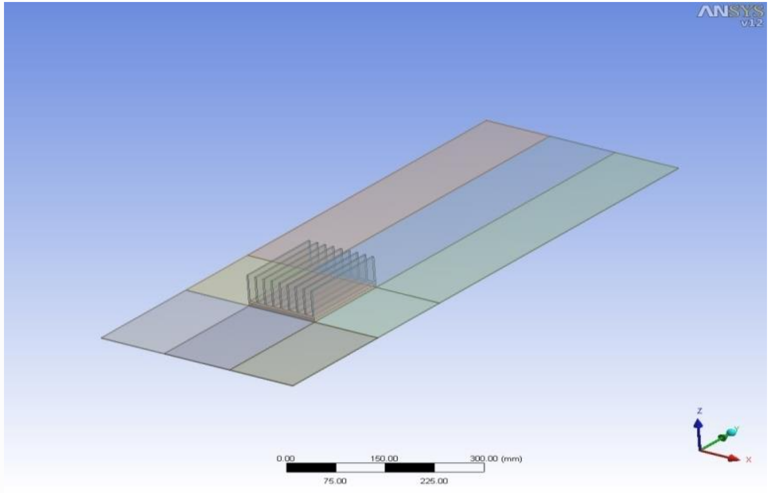
- When modelling heat transfer, you must provide :
  - Thermal conditions at walls and flow boundaries
  - Thermal properties for materials
- Available heat transfer modeling options include :
  - Species diffusion heat source
  - Combustion heat source
  - Conjugate heat transfer
  - Natural convection
  - Radiation
  - Periodic heat transfer

Workshop 05 Electronics Cooling

Dissipation of heat from a hot electronics component

- Conjugate Heat Transfer (CHT)
- Two runs
  - First run includes convection and conduction
  - Second run adds thermal radiation

The entire calculation takes a long time to run. So results are provided for post-processing.



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Appendix

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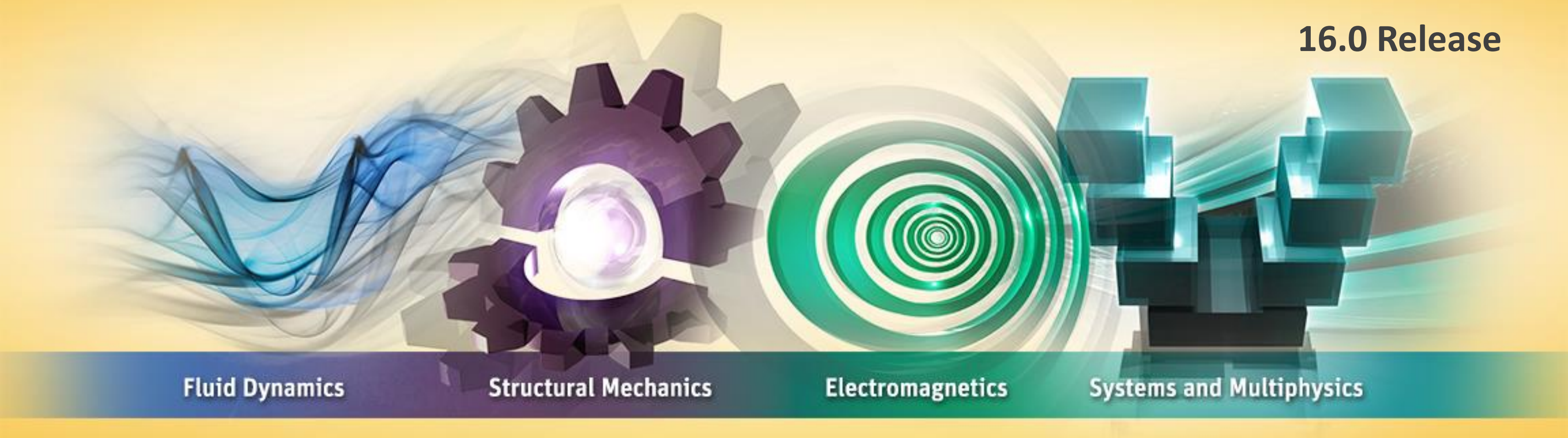

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Natural Convection

- **The significance of natural convection can be assessed through the Richardson number , Ri:**

$$Ri = \frac{g\beta\Delta TL}{U_0^{\,2}} = \frac{Natural}{Forced}$$

Ri = 1	$\Rightarrow$	Free and Forced convection effects must be considered
Ri << 1	$\Rightarrow$	Free convection effects may be neglected
Ri >> 1	$\Rightarrow$	Forced convection effects may be neglected

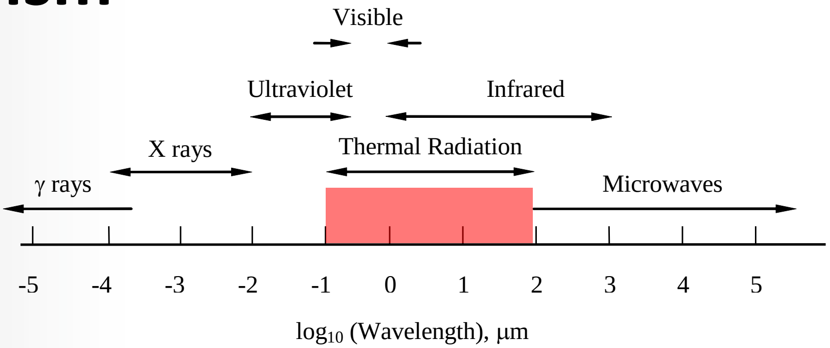
- **In buoyancy-driven flows, the Rayleigh number, Ra, indicates the relative importance of convection and conduction:**

$$Ra_x = \frac{g\beta\Delta Tx^3}{\nu\alpha} = \frac{buoyancy\ force}{viscous\ losses\ \&\ thermal\ diffusion}$$

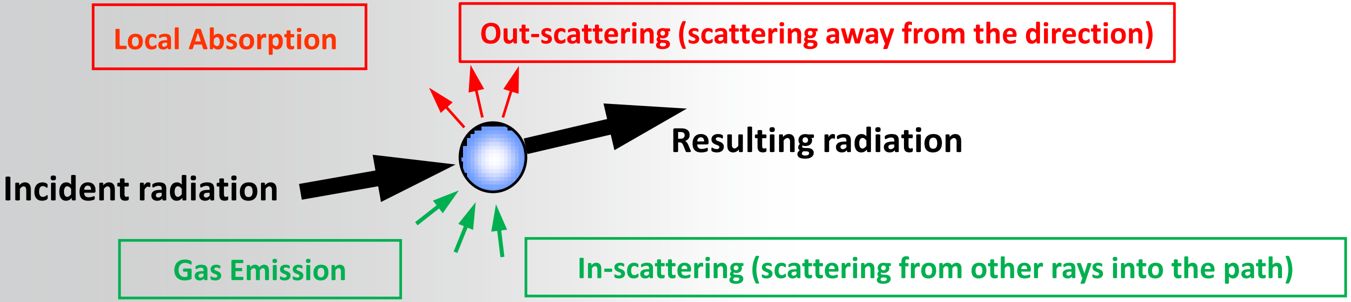
  - **The size of Ra is a measure of whether a natural convection boundary layer is laminar or turbulent. For a vertical surface the critical value is around 10^9 but the transition zone ranges from 10^6 to 10^9.**

Radiation: Mechanism

- Transfer of thermal energy by electromagnetic waves from 0.1 µm (ultraviolet) to 100 µm (mid-infrared).



- Radiation intensity is directionally and spatially dependent
- Transport mechanisms for radiation intensity along one given direction:



  - Scattering occurs when particles are present in the fluid - often neglected.

Radiation: Choice of Model

- The optical thickness should be estimated before choosing a radiation model
  - The optical thickness $\tau = a.L$
    - a is the absorption coefficient (m^{-1}) (Note: ≠ absorptivity of a surface)
    - L is the mean beam path length (m)
    - a = 0.25 to 0.3 m^{-1} for combustion product gases, = 0.01 m^{-1} for air and is proportional to absolute pressure
    - L is a typical distance between opposing walls
- Optically thin ($\tau < 1$) means that the fluid is partially transparent to thermal radiation
- Optically thick ($\tau > 1$) means that the fluid absorbs or scatters the radiation many times before it can interact with the surfaces

Radiation: Choice of Model

- For optically thick media (τ > 1) the P1 model is a good choice
  - Assumes radiative intensity is independent of direction
  - The P1 model gives reasonable accuracy without too much computational effort
- The Monte Carlo and Discrete Transfer models for any optical thickness
  - Both are ray tracing models
  - Discrete Transfer is much quicker as it pre-calculates rays in fixed directions but can be less accurate in models with long/thin geometries due to ray effects
  - Monte Carlo more expensive to run but recommended for complex geometries and multiband spectral modelling
- Surface to Surface Model
  - Available for Monte Carlo and Discrete Transfer models
  - Neglects the influence of the fluid on the radiation field
  - Can significantly reduce the solution time