Radiation Modeling In Fluid Flow

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Thanks to:
Erin Farbar, Jon Burt, Andrew Crow, Adam Irvine
Overview

- Fundamentals of radiation
- Approaches for numerical simulation:
  - Discrete Ordinance Method (DOM)
  - Monte Carlo Ray Tracing (MCRT)
- Illustrative examples:
  - Scramjet engine
  - Plume of a solid rocket motor
  - Radiation coupling with particle-laden turbulent flow
- Closing remarks
Radiation in Fluid Flows

- Radiation transport is an important phenomenon in many technology applications involving fluid flow, e.g.:
  - Combustion systems (efficiency, wall heating)
  - Rocket motors (plume signatures)
  - Solar collectors (energy conversion)
Fundamentals of Radiation (1)

- All matter with non-zero temperature emits thermal radiation with energy flux given by the Stefan-Boltzmann Law:

\[ \dot{q} = \varepsilon \sigma T^4 \text{ W/m}^2 \]

e.g., Sun: \( T = 5800 \text{ K} \), total radiated power = \( 4 \times 10^{26} \text{ W} \)!

- Due to large separation, solar flux at Earth = \( 1400 \text{ W/m}^2 \)

- Radiation is transmitted by photons (Duality):
  - Particles: momentum, energy (but zero mass!)
  - Waves: frequency, wavelength
  - Energy distribution (Planck spectrum)
Planck Radiation Spectrum
Fundamentals of Radiation Transport

• Radiation does not require a medium for transmission, but may interact with other media (optical depth):
  – Scattering (e.g., from solid particles)
  – Absorption (e.g., by molecules)

• Radiative spectral intensity, $I_\lambda(s, \Omega) \text{ W/sr/m}^2\text{/m}$
  – Varies by location, angle, and photon wavelength, $\lambda$
  – Source terms: emission and in-scattering
  – Sink terms: absorption and out-scattering
  – Absorption and emission based on same quantum structures
  – All terms are medium dependent
Radiative Transfer Equation (RTE)

\[
\frac{dI_\lambda(s, \tilde{\Omega})}{ds} + (\kappa_{p\lambda} + \kappa_{g\lambda}) I_\lambda(s, \tilde{\Omega}) + \sigma_{p\lambda} I_\lambda(s, \tilde{\Omega}) = \kappa_{p\lambda} I_{b\lambda}(T_p(s)) + \kappa_{g\lambda} I_{b\lambda}(T_g(s)) + \frac{1}{4\pi} \int \sigma_{p\lambda} P_{\lambda}(\tilde{\Omega}' \rightarrow \tilde{\Omega}) I_\lambda(s, \tilde{\Omega}') d\Omega'
\]

\(I_\lambda(s, \tilde{\Omega})\) - spectral intensity (W/sr/m²/m) at position \(s\) and direction \(\tilde{\Omega}\) and wavelength \(\lambda\)

\(I_{b\lambda}(T(s))\) - spectral blackbody intensity at temperature \(T\) and wavelength \(\lambda\) (W/sr/m²/m)

\(\kappa_{p/g\lambda}\) - particle/gas spectral absorption coefficient at wavelength \(\lambda\) (m⁻¹)

\(\sigma_{p\lambda}\) - particle spectral scattering coefficient at wavelength \(\lambda\) (m⁻¹)

\(P_{\lambda}(\tilde{\Omega}' \rightarrow \tilde{\Omega})\) - particle spectral scattering phase function
Radiative Transfer Equation (RTE)

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\(P_\lambda(\Omega' \rightarrow \Omega)\) - particle spectral scattering phase function

Spectral models needed for all wavelength dependent properties
Solution Techniques: Discretization Approaches

- Method of Spherical Harmonics ($P_N$ approximation)
  - Reduces the RTE to set of PDEs by expanding the radiation intensity in angular direction using spherical harmonics basis functions
  - Widely used due to relatively low computational cost
  - Solutions can exhibit non-physical oscillations in optically transparent regions

- Discrete Ordinates Method (DOM or $S_N$ approximation)
  - Reduces the RTE to set of PDEs by discretizing in angular coordinate
  - Spatial discretization can use a finite-volume approach
  - Suffers from ‘ray effects’ and ‘false scattering,’ latter more prominent at increasing optical thickness
Solution Techniques: Particle Approaches

- Monte Carlo Ray Tracing (MCRT)
  - Probabilistic, ‘bundles’ of photons are created at source(s) and tracked through domain
  - Exact solution of RTE but computationally expensive
  - Robust: Complex physics and boundary conditions are more easily included than in other methods

- Backward Monte Carlo (BMC)
  - Similar to MCRT, but rays traced backwards from detector to source
  - More efficient than MCRT if detectors are small relative to source
Verification Case 1

- Finite-length, diffusely reflecting parallel plates in large, cold environment
- 1.2M rays traced in each simulation
- Error in predicted radiative heat flux is <4% in all cases
- Statistical scatter increases with increasing $\epsilon$ as most rays are absorbed on plate without scattering, reducing total number of rays hitting each wall face

$T_{\infty} = 0, \ \epsilon_{\infty} = 1$

Normalized radiative heat flux from MCRT compared to exact solution (Modest, 2013)
Verification Case 2

• Infinite, diffusely reflecting parallel plates
• 1.2M rays traced in each simulation
• Error in predicted radiative volumetric absorption is <1% in both cases
• Radiative flux divergence calculated as
  \[
  \frac{dq}{d\tau} = \kappa \left( 4\pi I_b - G \right)
  \]
  
- \( G \) – incident radiation (W/m²)
- \( I_b \) – blackbody intensity (W/m²)

\[\tau = \kappa x\]

Normalized divergence of radiative heat flux from MCRT code compared to analytical solution (Modest, 2013)
1. HIFiRE-2 Scramjet: Combustor Wall Heating

- Hypersonic Flight Test (2012)
  - Joint AFRL/DTSO experiment
  - Single sounding rocket
  - JP7-air supersonic combustion
  - 4 inch wide rectangular cross section
- Ground Tests:
  - NASA Langley facility (HDCR)
  - Continuous run supersonic wind tunnel
  - Mach 6.5 flight equivalent flow conditions
  - 0.36-0.64 methane-ethylene fuel
  - Same combustion flow path as in flight test
Radiative Transfer Equation (RTE)

\[
\frac{dI_\lambda(s, \Omega)}{ds} + (\kappa_{\rho\lambda} + \kappa_{g\lambda}) I_\lambda(s, \Omega) + \sigma_{p\lambda} I_\lambda(s, \Omega)
= \kappa_{b\lambda} I_{b\lambda}(T_p(s)) + \kappa_{g\lambda} I_{b\lambda}(T_g(s)) + \frac{1}{4\pi} \int_{4\pi} \sigma_{p\lambda} P_{\lambda}(\Omega' \to \Omega') I_\lambda(s', \Omega') d\Omega'
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- \(I_{b\lambda}(T(s))\) - spectral blackbody intensity at temperature \(T\) and wavelength \(\lambda\) (W/sr/m²/m)

\(\kappa_{g\lambda}\) - gas spectral absorption coefficient at wavelength \(\lambda\) (m\(^{-1}\))

\(\sigma_{p\lambda}\) - particle spectral scattering coefficient at wavelength \(\lambda\) (m\(^{-1}\))

\(P_{\lambda}(\Omega' \to \Omega)\) - particle spectral scattering phase function

Absorption

Emission

Out-Scattering

Neglect particle (soot) effects

Decouple flow and radiation

Wall absorption and reflection

Optically thick in IR

In-Scattering

Neglect particle (soot) effects

Decouple flow and radiation

Wall absorption and reflection

Optically thick in IR
CFD Simulations

- Stanford LES
  - One quarter domain
  - 21 million cells
  - 500,000 timesteps
  - 17.3 ms simulation time
  - 11 species hydrocarbon progress variable combustion model

- AFRL RANS
  - One quarter domain
  - 1.4 million cells
  - k-ε RANS finite volume solver
  - Steady state fluid solutions
  - 22 species progress variable hydrocarbon combustion model
HIFiRE-2 RANS Solutions
Spectral Model

- Primary radiating species (IR): \( \text{H}_2\text{O}, \text{CO}_2 \)
- Wavelength dependence very complicated
  - 100 million+ known infrared features for water alone
- Absorptivity/emissivity (quantum coupling) depends on several factors
  - Wavelength
  - Temperature
  - Concentration
  - Pressure
- Several methods of spectral modeling
  - Monte Carlo Sampling (Line by Line)
  - Full spectrum approximations
  - Band modeling
Simulation Approach

- Discrete Ordinates Method (DOM)
  - Facilitated by simple geometry
  - Finite volume spatial mesh
  - Discrete ordinates angular mesh

- Solver
  - Full 3D, 2D, and axi-symmetric
  - First order flux transmission
  - Variable boundary conditions
    - Reflective, emissive, absorptive, periodic
  - Uncoupled from flowfield solver
    - Strictly post-processing of CFD
  - Banded spectral model
  - Parallelized in spectral space
  - Arbitrary number of radiative species
  - Adjoint sensitivity analysis
Radiation Simulations

• Radiative post-processing of CFD solutions using DOM
  – 90K point structured mesh (coarse grid)
  – $S_8$ ordinates method (80 directions)
  – 399 spectral bands
  – 5 radiative species ($H_2O, CO_2, CO, OH, CH_4$)
    – Scattering omitted
• Wall boundary conditions
• Heat transfer predictions
  – Wall heating
  – Energy absorption/emission by flow
Radiative Heat Flux Results

- Radiative heat flux to the walls
- Highest flux in cavity flameholder
Spectrally Resolved Wall Heat Flux
Volumetric Radiative Heat Flux
Validation Efforts

- Radiation measurements taken at NASA Langley
  - First hydrocarbon scramjet infrared measurements
  - 14 second experimental run time
  - 16 infrared photo-detectors at exit plane
  - 1.1-1.8 µm response function

- Radiation simulations
  - Direct experimental comparisons
  - Duplicate photo-detector field of view at exit plane
  - Processed all LES flowfields (41 snapshots)
  - Same spectral range
Comparisons

• Experimental results
  – Error bars 12–14%
  – Individually calibrated
• Computational predictions
  – Time-resolved and time-averaged LES
• Experimental agreement
  – Most trends followed
  – Overlapping magnitudes
  – Possible scattering effects

![Graph showing comparisons between time-averaged and time-resolved data with error bars for different sensor numbers.](image)
2. Bow Shock Ultra Violet-2 Rocket Plume Signature

- **BSUV-2 (1992) flight experiment on sounding rocket:**
  - Spectral radiance measured by onboard sensors
  - Primary payload measured bow shock emission (70 – 100 km)
  - Secondary payload detected plume radiation (100 - 115 km)

- **Solid rocket exhaust flow:**
  - $\text{Al}_2\text{O}_3$ particles, diameters 0.1-10 $\mu$m, 10-30% mass fraction
  - Supersonic gas mixture ($\text{H}_2$, $\text{N}_2$, $\text{O}_2$, CO)

- Plume radiation dominated by IR, but also some visible and UV emission

*Burt, “Monte Carlo Simulations of Solid Rocket Exhaust Plumes at High Altitude”*
Overall Simulation Approach

• Gas flow:
  – Ambient air (114 km altitude)
  – Rocket exit (H₂, N₂, O₂, CO)
  – Simulated using direct simulation Monte Carlo (DSMC)
  – Fully coupled to alumina particles (two-phase flow)

• Particle flow:
  – Size distribution from measurements
  – Lagrangian approach, coupled to DSMC and radiation

• Radiation requirements:
  – Optically thin gas, fully coupled to particles
  – Allow for particle field of arbitrary optical thickness
  – Spectral radiance evaluated at onboard sensor
Radiative Transfer Equation (RTE)

\[
\frac{dI_\lambda(s, \Omega)}{ds} + (\kappa_{p\lambda} + \kappa_{s\lambda})I_\lambda(s, \Omega) + \sigma_{p\lambda}I_\lambda(s, \Omega) = \kappa_{p\lambda}I_{b\lambda}(T_p(s)) + \kappa_{g\lambda}I_{b\lambda}(T_g(s)) + \frac{1}{4\pi} \int \sigma_{p\lambda}P_\lambda(\Omega' \rightarrow \Omega)I_\lambda(s, \Omega')d\Omega'
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- \(\kappa_{p\lambda}\) - particle spectral absorption coefficient at wavelength \(\lambda\) (m⁻¹)

- \(\sigma_{p\lambda}\) - particle spectral scattering coefficient at wavelength \(\lambda\) (m⁻¹)

- \(P_\lambda(\Omega' \rightarrow \Omega)\) - particle spectral scattering phase function

Optically thin gas
Full coupling between particles and radiation
Monte Carlo Ray Tracing

- Based on MCRT method of Farmer and Howell
- Energy bundles represent large number of photons over finite $\Delta \lambda$ range
- Created every few $\Delta t$ at randomly selected source particles
- Initial power based on $T_p$ and $\lambda$, direction assigned randomly
- Also created at inflow boundaries
Absorption coefficient in UV based on Anfimov et al.:
- Complicated functions of T
- Account for four overlapping mechanisms

Scattering coefficient based on Mie theory:
- Post-scatter photon angles sampled from Henyey-Greenstein distribution
Simulation Results

Contours of mass density for particles and gas
Particle Plume Properties

- Larger particles have smaller maximum divergence angle, higher temperatures
- Downstream reduction due to convective, radiative heat transfer
- Temperature jump due to crystallization
Radiation Results

- Emissive power concentrated in IR range
- Far greater intensity in nearfield region
- Downstream reduction due to divergence of path lines
- Greater temperature dependence for intensity in UV range
Validation Efforts

UV spectral radiance at onboard sensor

![Graph showing UV spectral radiance at onboard sensor]
3. Particle Laden Turbulent Flow Similar to Solar Collector

• Particles loaded into turbulent gas flow and allowed to mix:
  – Coupling between particle and turbulent dynamics
• Subsequently exposed to radiation source:
  – Heat transfer to particles that transfer energy to gas affecting turbulent flow
• Goals for radiation modeling:
  – Accurate prediction of photon transport in complex, multi-phase medium
  – Exa-scale implementation
  – V & V, UQ
Radiative Transfer Equation (RTE)

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\frac{dI_\lambda(s, \Omega)}{ds} + (\kappa_{p\lambda} + \kappa_{s\lambda}) I_\lambda(s, \Omega) + \sigma_{p\lambda} I_\lambda(s, \Omega) = \kappa_{p\lambda} I_{b\lambda}(T_p(s)) + \kappa_{g\lambda} I_{b\lambda}(T_g(s)) + \frac{1}{4\pi} \int_{4\pi} \sigma_{p\lambda} P_\lambda(\Omega' \rightarrow \Omega) I_\lambda(s, \Omega') d\Omega'
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- \( \kappa_{p\lambda} \) - particle spectral absorption coefficient at wavelength \( \lambda \) (m⁻¹)

- \( \sigma_{p\lambda} \) - particle spectral scattering coefficient at wavelength \( \lambda \) (m⁻¹)

- \( P_\lambda(\Omega' \rightarrow \Omega) \) - particle spectral scattering phase function

Optically thin gas
Full coupling between particles and radiation
Non-Dimensional Parameters: System Energy Coupling

\[ \Sigma = \frac{\rho_f C_f T_f}{\alpha c \tau_p} \]

• Radiation time scale:
  – \( \alpha \) = radiation power absorbed by a particle, \( c \) = particle concentration, \( \tau_p \) = particle aerodynamic relaxation time
  – Measures efficiency of coupling energy from particles to fluid
  – **PSAAP II**: \( \Sigma = 4\text{-}80 \), indicates strong coupling

• Shadow fraction: SF
  – Ratio of total particle cross section area to domain cross section area
  – **PSAAP II**: \( SF = 0.1\text{-}1.0 \), indicates semi-transparent optical regime

• Biot number: \( Bi = \frac{h L_c}{k} \)
  – Ratio of surface to internal thermal conductivities of a particle
  – **PSAAP II**: \( Bi << 1 \), indicates particles are isothermal
Non-Dimensional Parameters: Radiation-Particle Interaction

- Dimensionless optical thickness: $\kappa L_1$ ($L_1$=turbulent length scale, $\kappa$=absorption coefficient)
  - $\kappa L_1 \ll 1$ fluctuations in absorption coefficient and radiative intensity uncorrelated (no Turbulent Radiation Interaction, TRI)
  - PSAAP II: $\kappa = 0.7 \text{ m}^{-1}$ at 1$\mu$m, $L_1$ from turbulent structures

- Size parameter: $x = \pi d_p / \lambda$ ($d_p$=particle diameter)
  - $x \ll 1$ Rayleigh scattering, $x=1$ Mie scattering, $x \gg 1$ geometric optics
  - PSAAP II: $x = O(10)$, indicates geometric optics regime

- Clearance ratio: $c / \lambda$ ($c$=average clearance between particles)
  - $> 0.5$ implies scattering of one particle unaffected by others
  - PSAAP II: $c / \lambda \sim 125$, indicates use of “cloud of particles” model
Spectral Model for Nickel

- Nickel particles (12 µm) interacting with infrared radiation (λ = 0.7–3 µm)
  - Use geometric optics for the absorption and scattering coefficients (κ_{pλ} and σ_{pλ}) for particle clouds
- Smooth particle surfaces will lead to nearly isotropic Φ
- Extremely rough particle surfaces with characteristic dimension ~λ will give strong back-scattering peak in Φ

Spectral hemispherical reflectance (ρ_{λ}) for nickel. Absorptance, α_{λ}=1-ρ_{λ}
Overall PSAAP-2 Simulation Approach

Fluid Model ↔ Particle Model ↔ Radiation Model

Discrete Particles
- MCRT

Cloud of Particles
- DOM
- MCRT
Cost Versus Accuracy

- MCRT: expensive but most accurate (“exact”)
- DOM: cheaper but less accurate
- Recent comparison of DOM to MCRT for industrial burner application [1]:
  - MCRT required 40x more computational resources than DOM LC11 (96 directions)
  - MCRT employed at a few select points to evaluate error in DOM
  - Maximum error between MCRT and DOM solution was 10% in most optically thick region of domain
- MCRT may be more parallel efficient in exa-scale environment

Challenges for Validation

- Detailed characterization of particles:
  - Spectral properties, size distribution, loading

- Detailed characterization of radiation source:
  - Output intensity spectrum
  - Angular distribution

- Characterization of facility:
  - Spectral properties of all solid surfaces

- Selection of diagnostics:
  - What system properties can be measured that will discriminate between different radiation models?
Closing Remarks

• Radiation is an important process in many fluid flows
• Numerical simulation is made challenging by the variety of physical mechanisms (absorption, emission, scattering)
• Various computational techniques exist that are best suited for different levels of physical and geometric complexity
• Spectral modeling is a key aspect of all radiating systems
• Many opportunities for verification using simple test cases
• Validation requires carefully designed experiments with suitable diagnostics
Questions?
Backup Slides
Energy Absorbed by Medium
Non-Dimensional Parameters: Radiation-Particle Interaction

- **Dimensionless optical thickness**: $\kappa L_I$ ($L_I$=turbulent length scale, $\kappa$=absorption coefficient)
  - $\kappa L_I << 1$ fluctuations in absorption coefficient and radiative intensity uncorrelated
  - **PSAAP II**: $\kappa = 0.7 \text{ m}^{-1} \text{ at 1}\mu\text{m}$, $L_I$ determined by turbulent structures

- **Size parameter**: $x = \frac{\pi d_p}{\lambda}$ ($d_p$=particle diameter)
  - $x<<1$ Rayleigh scattering, $x=1$ Mie scattering, $x>>1$ geometric optics (with $kx>>1$)
  - **PSAAP II**: $x=O(10)$ with $kx=O(10)$, indicates geometric optics regime

- **Complex index of refraction**: $m = n - ik$ ($n$=index of refraction, $k$=index of absorption)
  - reflection increases with $n$, absorption increases with $k$
  - **PSAAP II**: for nickel, $m = 2.85 - i5.1$ at 1$\mu$m

- **Clearance ratio**: $c / \lambda$ ($c$=clearance between particles)
  - $> 0.5$ indicates scattering of one particle unaffected by the presence of others, allows use of ‘cloud’ of particles model
  - **PSAAP II**: $c / \lambda \sim 125$, indicates independent scattering at uniform loading
Spectral Model for Particles

- When \( kx < 10 \) and \( x = O(1) \), spectral properties of a ‘cloud’ of particles is used to model particle interaction with radiation
  - Mie theory:
    - Complicated functions for \( \kappa_{p\lambda}, \sigma_{p\lambda}, P_{\lambda}(\Omega' \to \Omega) \)
    - \( P_{\lambda}(\Omega' \to \Omega) \) may be simplified by assuming isotropic scattering, linear anisotropic scattering, etc.

Image from Modest, “Radiative Heat Transfer,” 2013
Interaction of Radiation with Particles

- Particles can diffract, refract, absorb and reflect radiation.

- Non-dimensional parameters that define the spectral model used for the particles:
  \[ m = n - ik \]
  \[ c/\lambda \]
  \[ x = 2\pi a / \lambda \]
  \[ kx \]

Image from Modest, “Radiative Heat Transfer,” 2013
Simplifications to Mie Theory For Spectral Model

- If $|m-1| << 1$ and $k \approx 0$
  - Leads to Rayleigh-Gans scattering for near-dielectric sphere
  - Simplifies spectral relations for particles dramatically
- If $|m-1|<< 1$ for $x>>1$ and $k \approx 0$
  - van de Hulst relation for anomalous diffraction may be used to simplify spectral relations
- If $x>>1$ and $kx>>1$: Geometric optics
  - For dielectric particles ($k \sim 0$), this means $x=10000$
  - For metal particles, this means $x=10$
- If $x << 1$: Rayleigh scattering (for example, soot particles)
- Non-uniform particle sizes smooth the oscillations in the phase function, making the computation less complicated

Particle size and material have a strong effect on the type of spectral model that is required
5 Year Plans

• Investigate methods for coupling high-fidelity radiation model to point-particle and particle resolved simulations
• Validate coupled predictions with experimental data
• Assess cost and accuracy relative to P1 or 6-flux model
• Investigate sensitivity of results to particle-grid interpolation methods (baseline, higher order)
• Reassess assumptions made in spectral model, including assumption of independent scattering
• Algorithm improvement (efficiency, scalability)
• Investigate sub-grid radiation modeling
1D media between parallel plates, analytical solutions

Case 1: no participating media, grey plates
Case 2: isotropic and anisotropic scattering, cold black plates
Case 3: emitting, absorbing, isotropic scattering, cold black plates
Case 4: isotropic scattering, grey plates
Case 5: emitting and absorbing, grey plates

3D benchmark solution

Case 1: grey, nonhomogeneous, absorbing, emitting, non-scattering media between cold black surfaces

Grid-Based Spectral Properties

Currently implemented in MCRT:
• particle P contributes only to spectral properties in cell 1

Possible improvement:
• particle P contributes to spectral properties in cells 1-4
• contributions weighted by distance from P to each cell center
Coupling Strategy

• Call radiation solver every \((|v_p|/\Delta x_{rad})^{-1}/\Delta t_{\text{CFD}}\) iterations [1]


• Black (fine) grid is used for turbulent flow simulations, red (coarse) grid is used to compute radiative heat fluxes.
Coupling Strategy (2)

• Communicate direction-averaged radiative flux for particles in each cell

\[
q_{rad} = \sum_{i=1}^{N_\eta} \left[ \alpha_i \int I_\eta d\Omega - 2hc_o^2 \int \int \frac{\eta^3 \alpha_i}{4\pi e^{hc_0\eta/kT} - 1} d\eta d\Omega \right] \text{ W/m}^2
\]

The first term is the radiative flux absorbed by particles, the second term is the radiative flux emitted by particles.

\(N_\eta\) – number of wave number bins under consideration
\(\alpha_i\) – absorptance for bin \(i\)
\(h\) – Plank’s constant, J-s
\(c_o\) – speed of sound in vacuum, m/s
\(k\) – Boltzmann’s constant, J/K
\(\Delta\eta_i\) – width of wavenumber bin \(i\), m\(^{-1}\)

(refractive index of air, \(n \approx 1\))
• The radiation source term for a single particle is then

\[ Q_p = \pi R_p^2 q_{\text{rad}} \quad \text{W} \]

\(R_p\) – radius of particle, m

• May investigate interpolating \(q_{\text{rad}}\) from coarse mesh onto fine turbulent flow mesh
• Modeling efforts for particle-laden, turbulent, radiating flows focused in several application areas:
  – Combustion systems (flames, solid rocket motors, etc.)
  – Rocket plumes
  – Atmospheric processes (e.g., aerosols, clouds)
  – Fire containment
  – Solar receivers

• Efforts to-date for solar-receiver modeling are relatively simple, usually commercial software packages are used

• Combustion modeling seems to be the most advanced (DNS with high-order photon Monte Carlo modeling)
• State-of-the-Art modeling capabilities for these systems can be divided into three categories
  – Method used to solve RTE (the solver)
    • Some variation of photon Monte Carlo model or DOM are most common
  – Spectral model for participating media (gas, particles)
    • Correlations from experiment, gray-gas approximation, correlated-k or line-by-line method for absorption properties
    • No scattering, isotropic scattering, linear anisotropic scattering or full solution from Mie theory
    • Spherical; constant, discrete or distribution of diameters
  – Radiation – turbulence interaction (RTI)
    • Typically turbulence is only accounted for by an enhanced thermal conductivity in the fluid model, or by including temperature fluctuations only in emission terms (i.e., assuming $\kappa L_i << 1$)
    • In flame modeling, full DNS has been used
• The next few slides show some examples