# Heat and mass transfer in high-temperature particle–gas flows under high-flux irradiation

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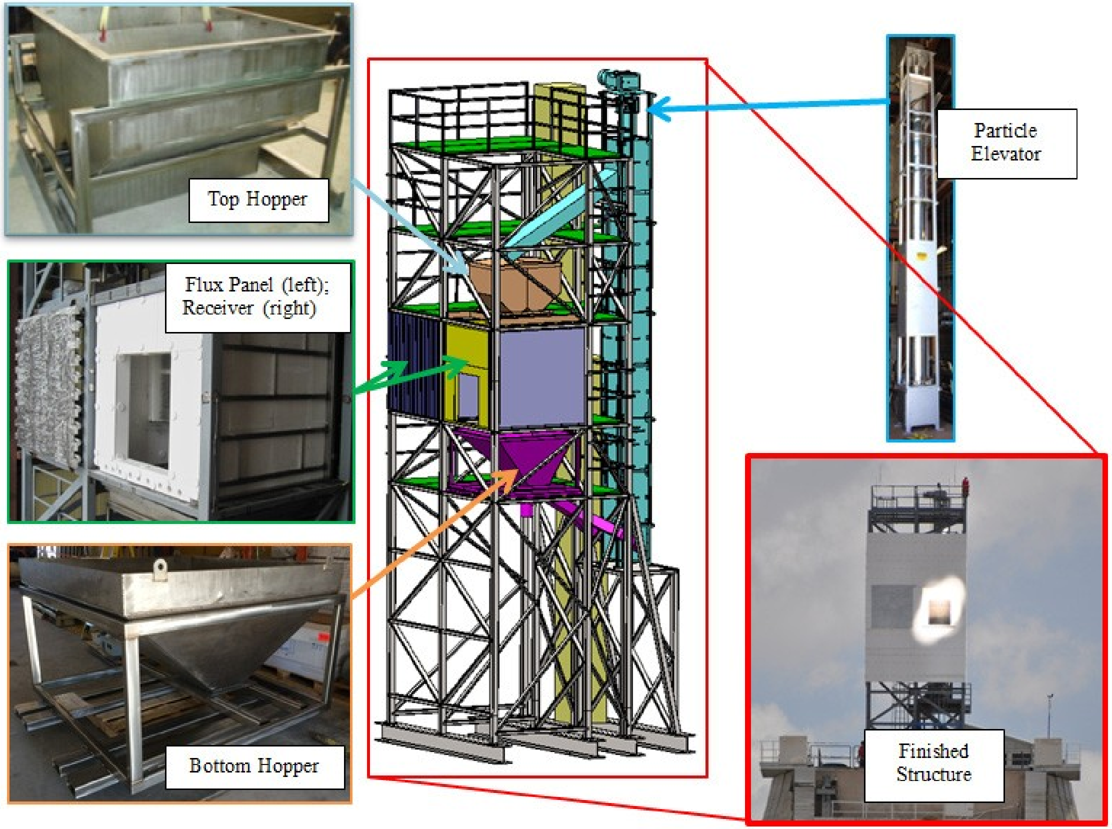
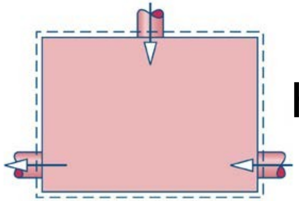
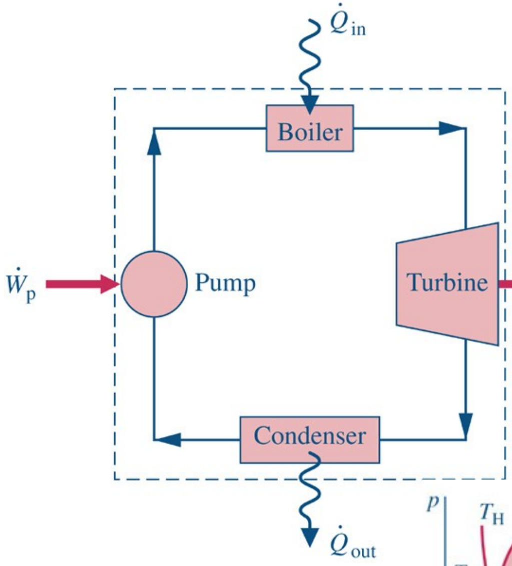
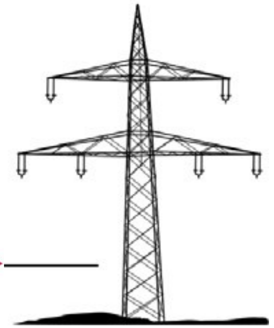
# Overview of solar power plant

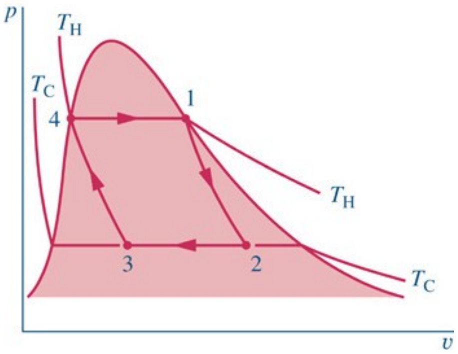


Heat exchanger



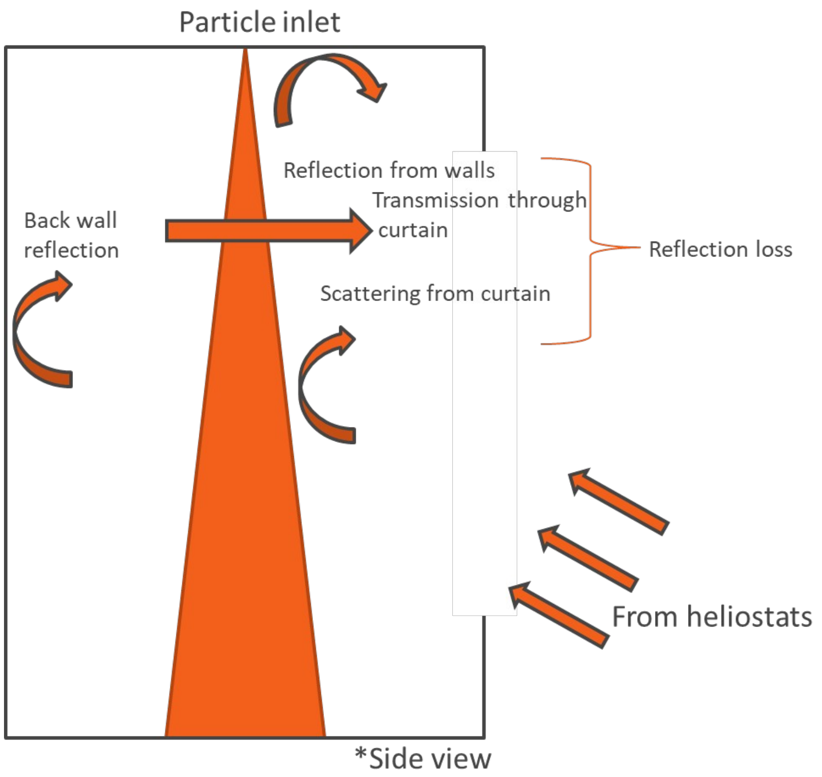






M.J. Moran, et al. Fundamentals of engineering thermodynamics. 2010.

# Falling particle receivers

- Falling particle receivers (FPRs) are a leading technology to couple with next generation CSP systems
- FPRs release a curtain of particles as the working fluid that are heated as they fall past the beam of concentrated solar radiation
- Advantages:
    1) Can achieve high particle temperatures
    2) High thermal efficiency
    3) Low cost transfer medium
    4) Efficient storage

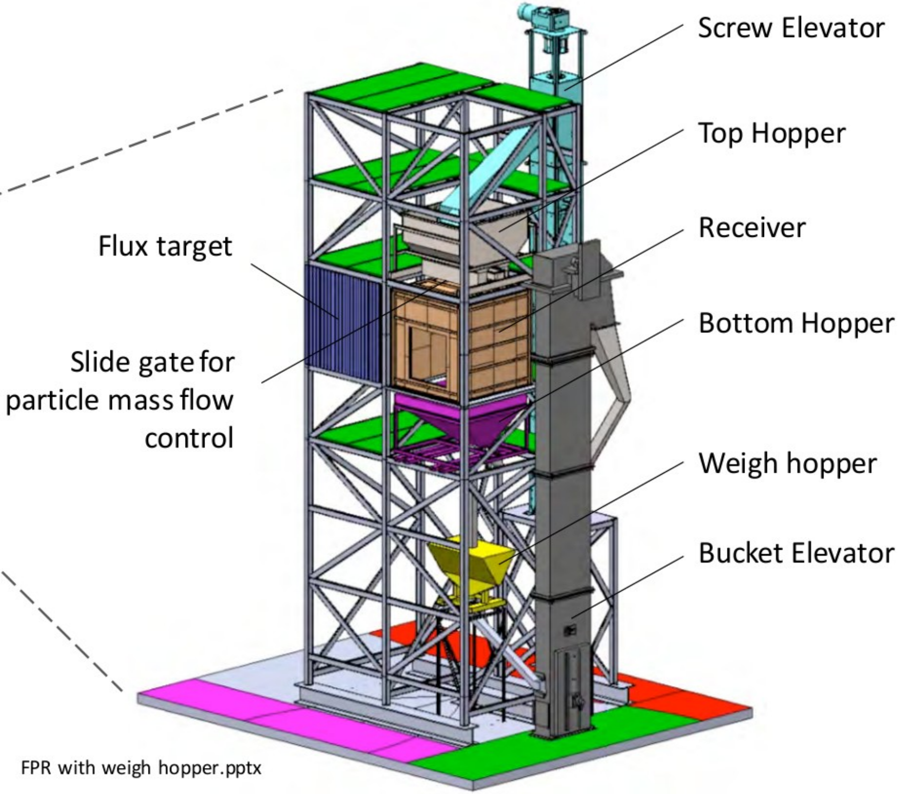




J. Coventry, et al., AIP Conference Proceedings, 1850 (2017): 030011
C.K. Ho, US Patent App. 16/700,134 (2020)C. Ho, Applied Thermal Engineering, 2016.
A. Kumar et al., ASME Journal of Solar Energy Engineering, 2018.
A. Kumar et al., International Journal of Heat and Mass Transfer, 2019.

# Free-falling particle receiver (SNL)

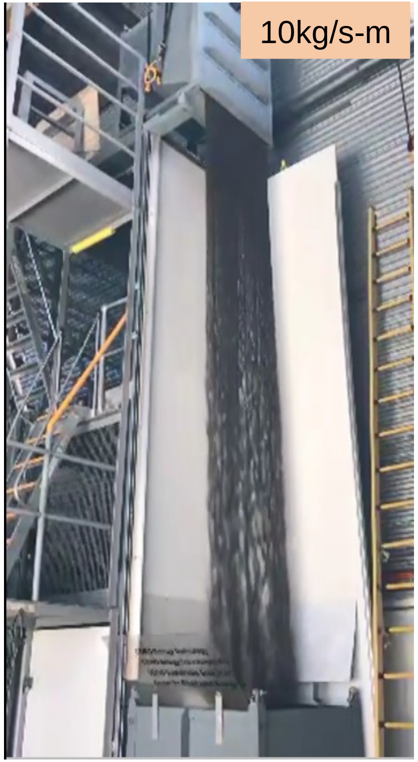
- Gen3 particle receiver & on-sun test

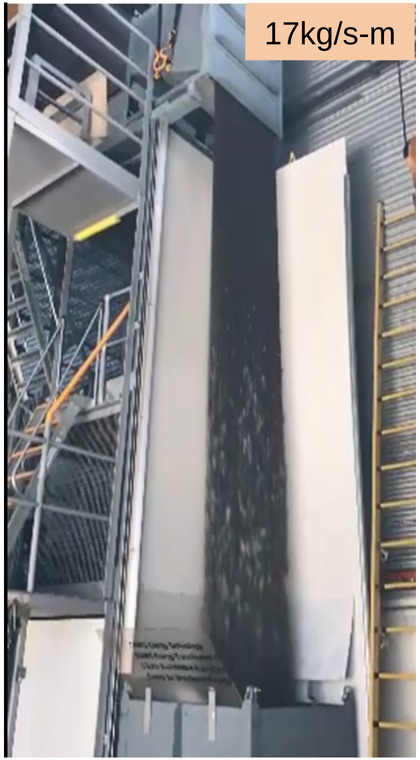



CARBO HSP particles
- ~350  m diameter
- ~0.9 solar absorptivity

C.K. Ho, US Patent App. 16/700,134 (2020)
C. Ho, Applied Thermal Engineering, 2016.

# Multi-stage receiver (CSIRO)

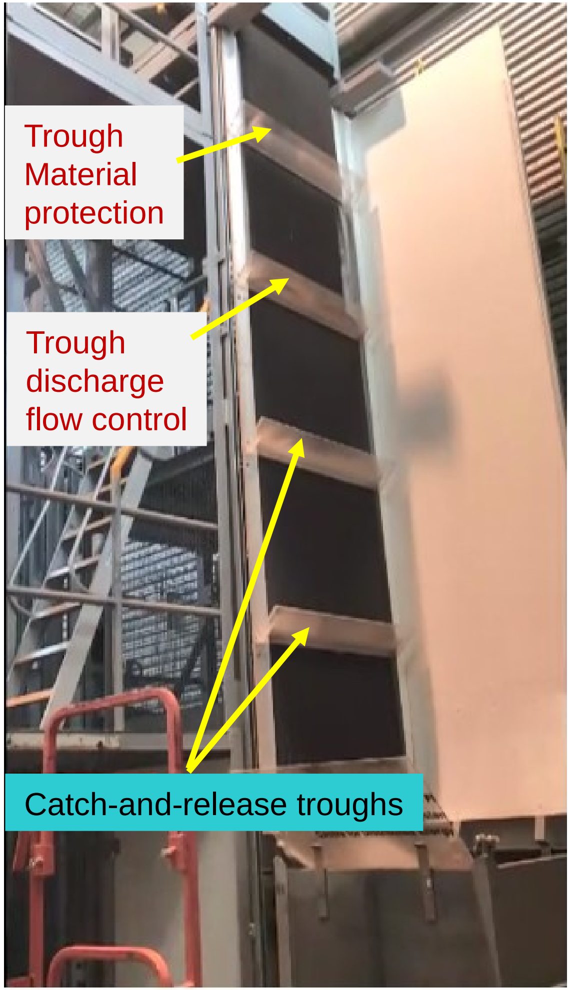




Free-falling particles:

- Decreased absorptance
- Flow instability
- Uneven heating
- Air entrainment

Multi-stage falling




J.-S. Kim et al., SolarPACES, 2019.

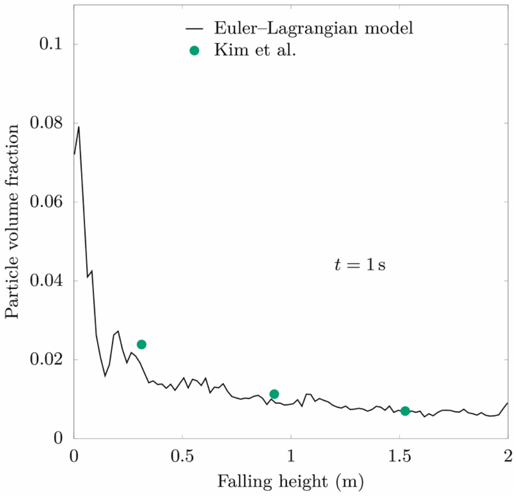
# Multi-phase flow

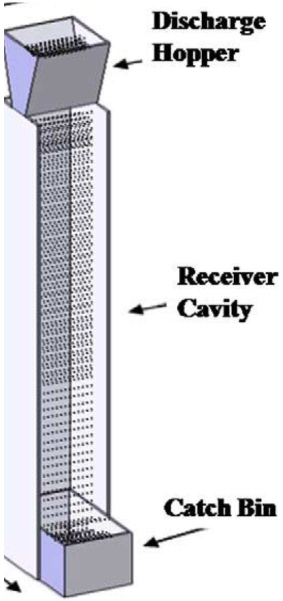
- Gas phase

Euler

$$\frac{\partial}{\partial t}(\varepsilon_{\mathrm{g}}\rho_{\mathrm{g}}) + \frac{\partial}{\partial x_i}(\varepsilon_{\mathrm{g}}\rho_{\mathrm{g}}u_{\mathrm{g}i}) = 0$$

$$\frac{\partial}{\partial t}(\varepsilon_{\mathrm{g}}\rho_{\mathrm{g}}u_{\mathrm{g}i}) + \frac{\partial}{\partial x_j}(\varepsilon_{\mathrm{g}}\rho_{\mathrm{g}}u_{\mathrm{g}j}u_{\mathrm{g}i}) = -\varepsilon_{\mathrm{g}}\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{\mathrm{g}ij}}{\partial x_j} - F_i + \varepsilon_{\mathrm{g}}\rho_{\mathrm{g}}g_i$$




- Particle phase

$$\frac{\partial f}{\partial t} + \sum_i \left[\frac{\partial (f u_{\mathrm{p}i})}{\partial x_i} + \frac{\partial (f A_i)}{\partial u_{\mathrm{p}i}}\right] = 0$$

$$\varepsilon_{\mathrm{p}} = \int\int f \frac{m}{\rho_{\mathrm{p}}} \mathrm{d}m \Pi_j \mathrm{d}u_{\mathrm{p}j}$$

$\longrightarrow$

$$\frac{\partial(\varepsilon_{\mathrm{p}}\rho_{\mathrm{p}})}{\partial t} + \frac{(\varepsilon_{\mathrm{p}}\rho_{\mathrm{p}}\bar{u}_{\mathrm{p}i})}{\partial x_i} = 0$$

$$\frac{\partial(\varepsilon_{\mathrm{p}}\rho_{\mathrm{p}}\bar{u}_{\mathrm{p}i})}{\partial t} + \frac{(\varepsilon_{\mathrm{p}}\rho_{\mathrm{p}}\bar{u}_{\mathrm{p}i}\bar{u}_{\mathrm{p}i})}{\partial x_i} = -\varepsilon_{\mathrm{p}}\frac{\partial p}{\partial x_i} - \frac{\partial \tau}{\partial x_i} + \varepsilon_{\mathrm{p}}\rho_{\mathrm{p}}g_i$$
$$+ \int\int f m D(u_{\mathrm{g}i} - u_{\mathrm{p}i}) \mathrm{d}m \mathrm{d}u_{\mathrm{p}j} - \frac{\partial\left[\int\int f m (u_{\mathrm{g}i} - u_{\mathrm{p}i})(u_{\mathrm{g}i} - u_{\mathrm{p}i}) \mathrm{d}m \mathrm{d}u_{\mathrm{p}j}\right]}{\partial x_i}$$

Multiphase particle-in-cell


M. Syamlal, W. Rogers, T. O’Brien, MFIX documentation theory guide, 1993

M.Andrews, P. O’Rourke, Int. J. Multiphase Flow, 22 (1996): 379–402

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K. Kim, N. Siegel, et al., Solar Energy 83 (2009): 1784–1793

# Heat transfer

- Gas phase

$$\varepsilon_{\mathrm{g}}\rho_{\mathrm{g}}c_{p,\mathrm{g}}\left(\frac{\partial T_{\mathrm{g}}}{\partial t}+u_{\mathrm{g}j}\frac{\partial T_{\mathrm{g}}}{\partial x_j}\right)=-\frac{\partial q''_{\mathrm{g}i}}{\partial x_i}-\frac{\partial q''_{\mathrm{c}i}}{\partial x_i}$$

$$q''_{\mathrm{g}i}=-\varepsilon_{\mathrm{g}}k_{\mathrm{g}}\frac{\partial T_{\mathrm{g}}}{\partial x_i}$$

$$-\frac{\partial q''_{\mathrm{c}i}}{\partial x_i}=6\varepsilon_{\mathrm{p}}\frac{\sum_{m=1}^{N_{\mathrm{p}}}n_{\mathrm{p},m}d_{\mathrm{p},m}^2h_{\mathrm{p,g}}(T_{\mathrm{p},m}-T_{\mathrm{g}})}{\sum_{m=1}^{N_{\mathrm{p}}}n_{\mathrm{p},m}d_{\mathrm{p},m}^3}$$

- Particle phase

$$n_{\mathrm{p},i}mc_{v,\mathrm{p}}\frac{\mathrm{d}T_{\mathrm{p},i}}{\mathrm{d}t}=q_{\mathrm{c},i}+\underline{q_{\mathrm{r},i}},$$

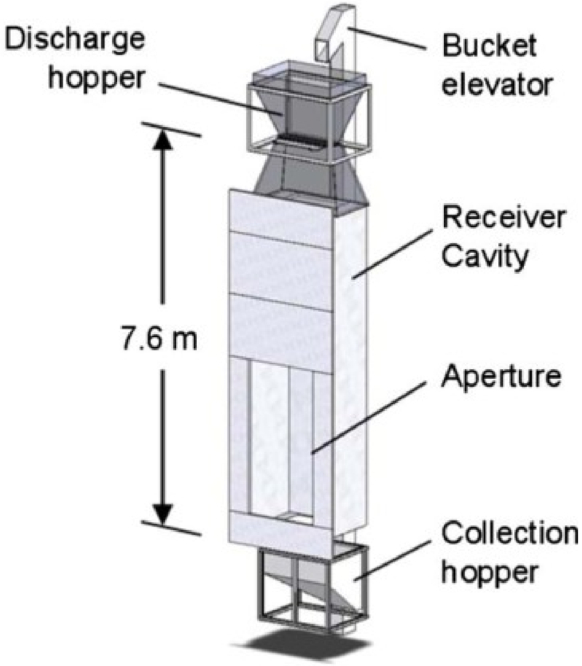
$$q_{\mathrm{c},i}=n_{\mathrm{p},i}h_{\mathrm{p,g}}\pi d_{\mathrm{p},i}^2(T_{\mathrm{g}}-T_{\mathrm{p},i})$$

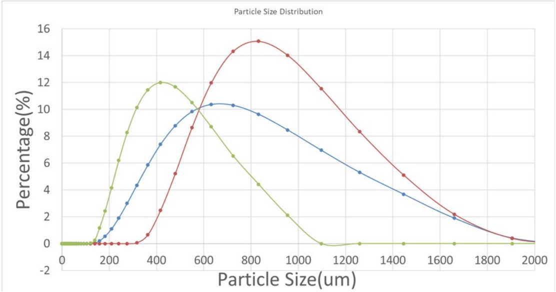
$$\underline{q_{\mathrm{r},i}}=n_{\mathrm{p},i}\pi d_{\mathrm{p},i}^2\underline{q''_{\mathrm{r},i}}$$

M. Syamlal, W. Rogers, T. O'Brien, MFIX documentation theory guide, 1993

# Radiative heat transfer

Australian National University

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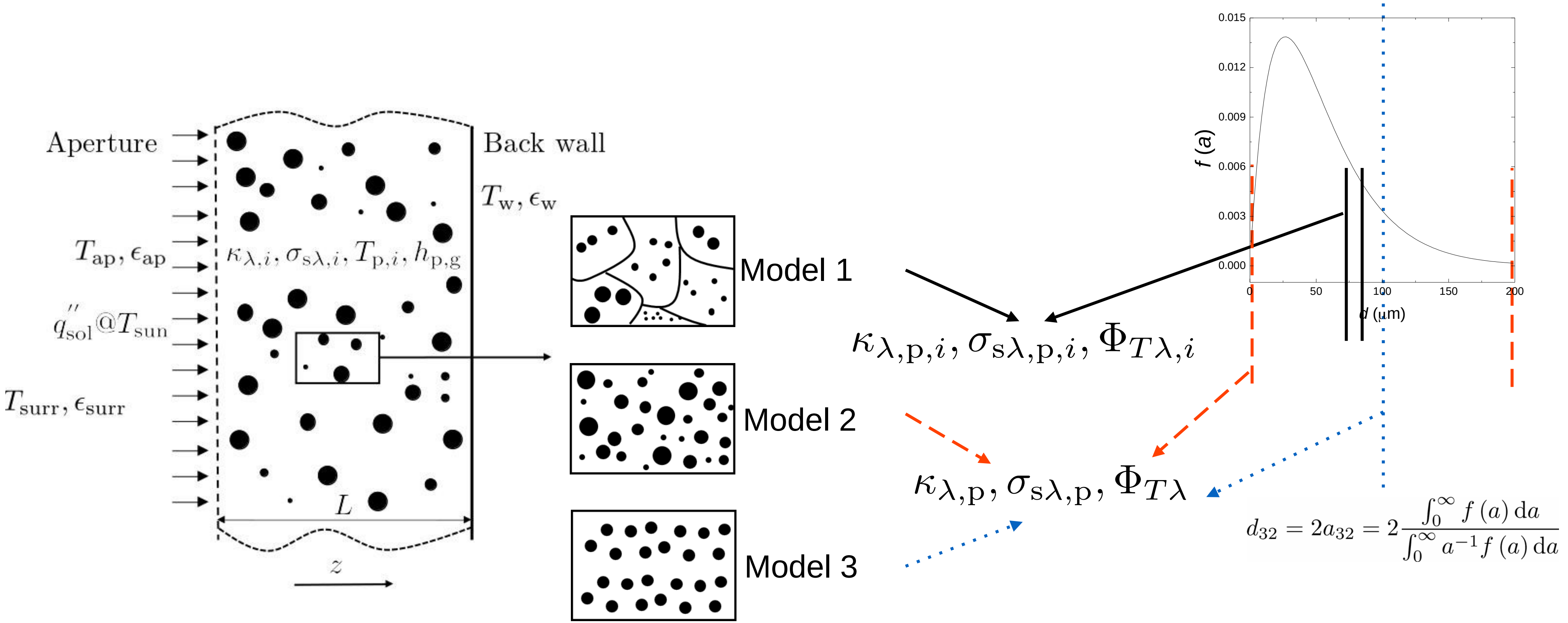
W. Lipiński, et al., Numerical Heat Transfer, Part B, 47 (2005): 443–457

A. Kumar, et al., International Journal of Heat and Mass Transfer, 146 (2020): 118821

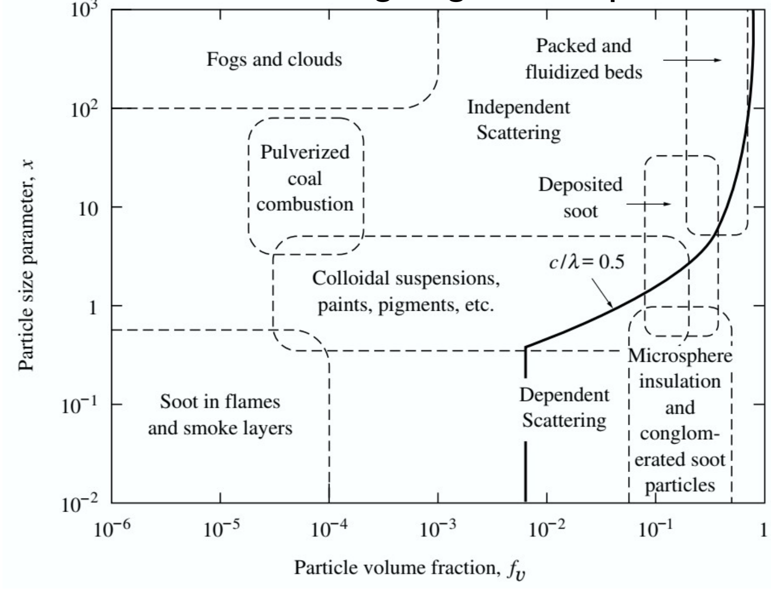
## Light–matter interactions in polydispersions

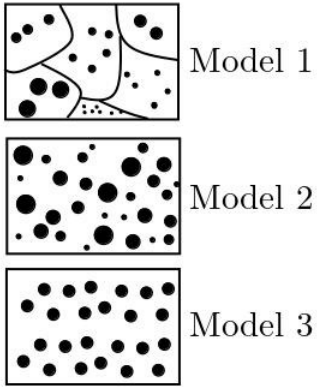
# Radiative heat transfer

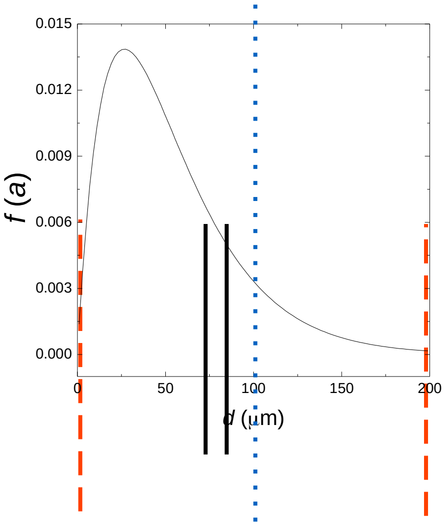


# Radiative heat transfer

Scattering regime map




$(a_{\min,i}, a_{\max,i})$ $(0, a_{\max})$

$$\{\sigma_s, \kappa, \beta\}_{\lambda,i} = \frac{3}{4}\int_{a_{\min,i}}^{a_{\max,i}} \{Q_{\text{sca}}, Q_{\text{abs}}, Q_{\text{ext}}\} a^{-1} f(a) f_v \, \mathrm{d}a, \ \text{App. 1 \& 2}$$

Mie theory

$$\frac{3 f_v}{2 d_{32}} \{Q_{\text{sca}}, Q_{\text{abs}}, Q_{\text{ext}}\}, \ \text{App. 3}$$


C.L. Tien, et al., Annual Review of Numerical Fluid Mechanics and Heat Transfer, 1 (1987): 1–32

M.F. Modest, Radiative Heat Transfer, 2013

C. Bohren, et al., Absorption and Scattering of Light by Small Particles, 2008

# Radiative heat transfer

- Radiative transfer equation

$$\frac{\mathrm{d}I_\lambda}{\mathrm{d}s} = \sum_{i=1}^{M} \kappa_{\lambda,i} I_{\mathrm{b}\lambda,i}(T_{\mathrm{p},i}) - \left(\sum_{i=1}^{M} \beta_{\lambda,i}\right) I_\lambda + \frac{1}{4\pi}\int_{4\pi} \left(\sum_{i=1}^{M} \sigma_{\mathrm{s}\lambda,i} \bar{\Phi}_{\lambda,i}\left(\hat{\mathbf{s}}_j, \hat{\mathbf{s}}\right)\right) I_\lambda\left(\hat{\mathbf{s}}_j\right) \mathrm{d}\Omega_j$$

$$I_\lambda\left(z=0, \hat{\mathbf{s}}\right) = q_\lambda^{''} \delta(\hat{\mathbf{s}} - \hat{\mathbf{s}}_0)$$

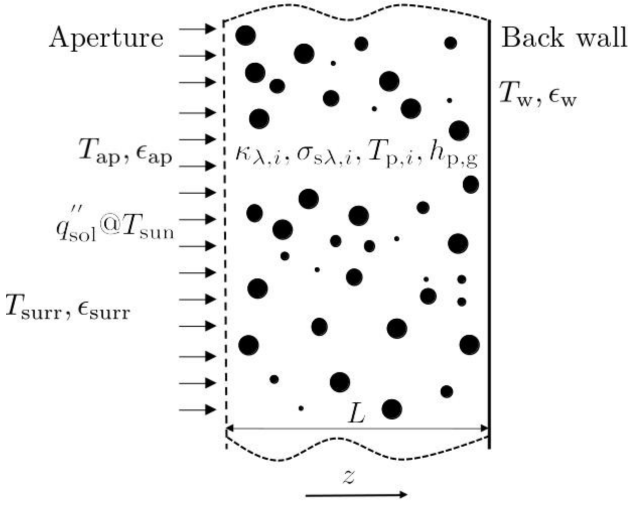
$$I_\lambda\left(z=L, \hat{\mathbf{s}}\right) = \epsilon_{\lambda,\mathrm{w}} I_{\mathrm{b}\lambda}\left(s\right) + \frac{\rho_{\lambda,\mathrm{w}}}{\pi}\int_{\hat{\mathbf{n}}\cdot\hat{\mathbf{s}}'<0} I_\lambda\left(s, \hat{\mathbf{s}}^{'}\right) |\hat{\mathbf{n}}\cdot\hat{\mathbf{s}}^{'}| \mathrm{d}\Omega^{'}$$

$$\nabla\cdot\mathbf{q}_{\mathrm{r}}^{''} = \int_0^\infty \int_{4\pi} \frac{\mathrm{d}I_\lambda}{\mathrm{d}s} \mathrm{d}\Omega\mathrm{d}\lambda = \int_0^\infty \kappa_{\lambda,\mathrm{p}}\left(4\pi I_{\mathrm{b}\lambda} - G_\lambda\right)\mathrm{d}\lambda$$

- Numerical solution
  - Monte Carlo ray-tracing

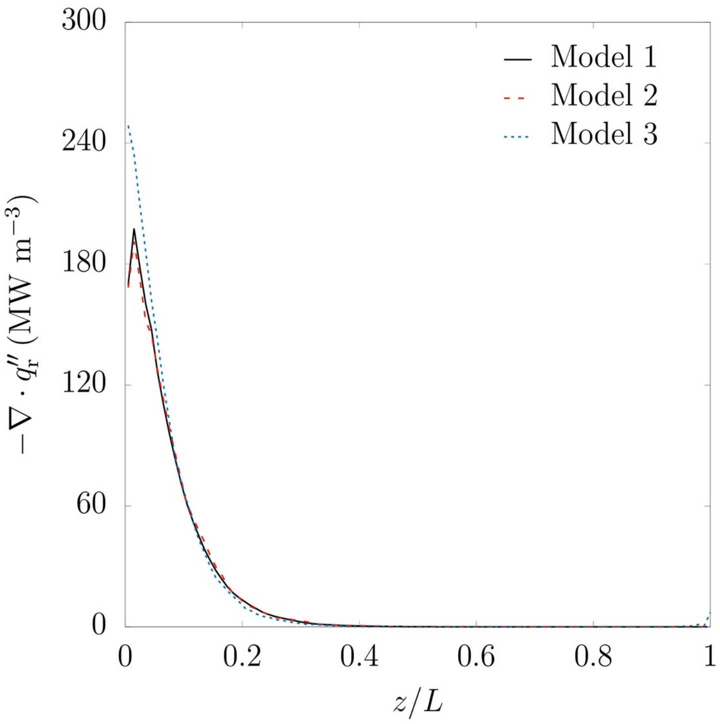
$$q_{\mathrm{r},i} = -\int_{V_i} \nabla\cdot\mathbf{q}_{\mathrm{r}}^{''}\mathrm{d}V = n_{\mathrm{a},i} q_{\mathrm{ray}} - \int_{V_i} 4\kappa_{\mathrm{P}}\sigma T^4 \mathrm{d}V$$

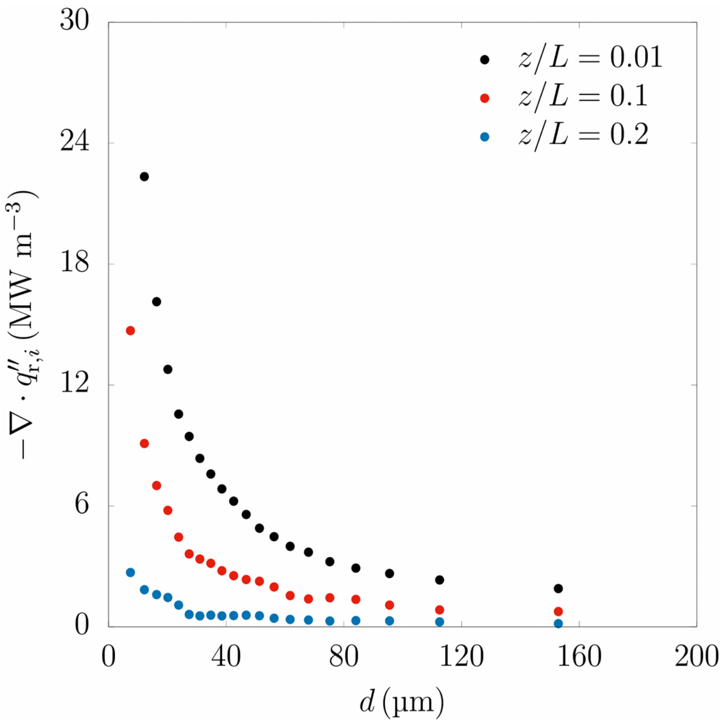
$$q_{\mathrm{r},j} = -\int_{A_j} \mathbf{q}_{\mathrm{r}}^{''}\cdot\hat{\mathbf{n}}\mathrm{d}A = n_{\mathrm{a},j} q_{\mathrm{ray}} - \int_{A_j} \epsilon\sigma T^4 \mathrm{d}A$$

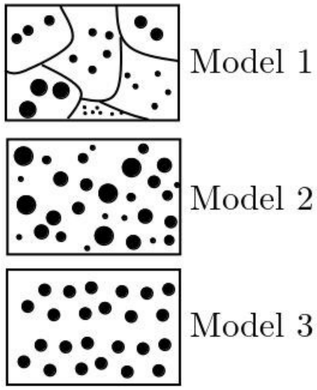



M.F. Modest, Radiative Heat Transfer, 2013

# Results: Radiative absorption




- Models 1 & 2 result in more intense radiation attenuation in the medium
- Radiation absorption in Model 3 is approximately 10% higher than in Models 1 & 2
- Strongly size-dependent radiation absorption is observed in Model 1

# Summary and conclusions

- Multiphase particle-in-cell method is applied for particle–gas hydrodynamics
- Radiative transfer in polydispersed media is investigated by three alternative approaches
- Multi-component radiative transfer model (Model 1) gives insights into size-dependent transport phenomena and thermal response
- Multi-component radiative transfer model (Model 1) is coupled with particle–gas hydrodynamics models based on multiphase particle-in-cell method

# Future work

- Experimental validation of the heat and mass transfer model
- Integration of the multi-component radiative transfer model (Model 1) with particle–gas flow in a full-scale particle receiver

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