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Radiative transfer in a free-falling particle receiver

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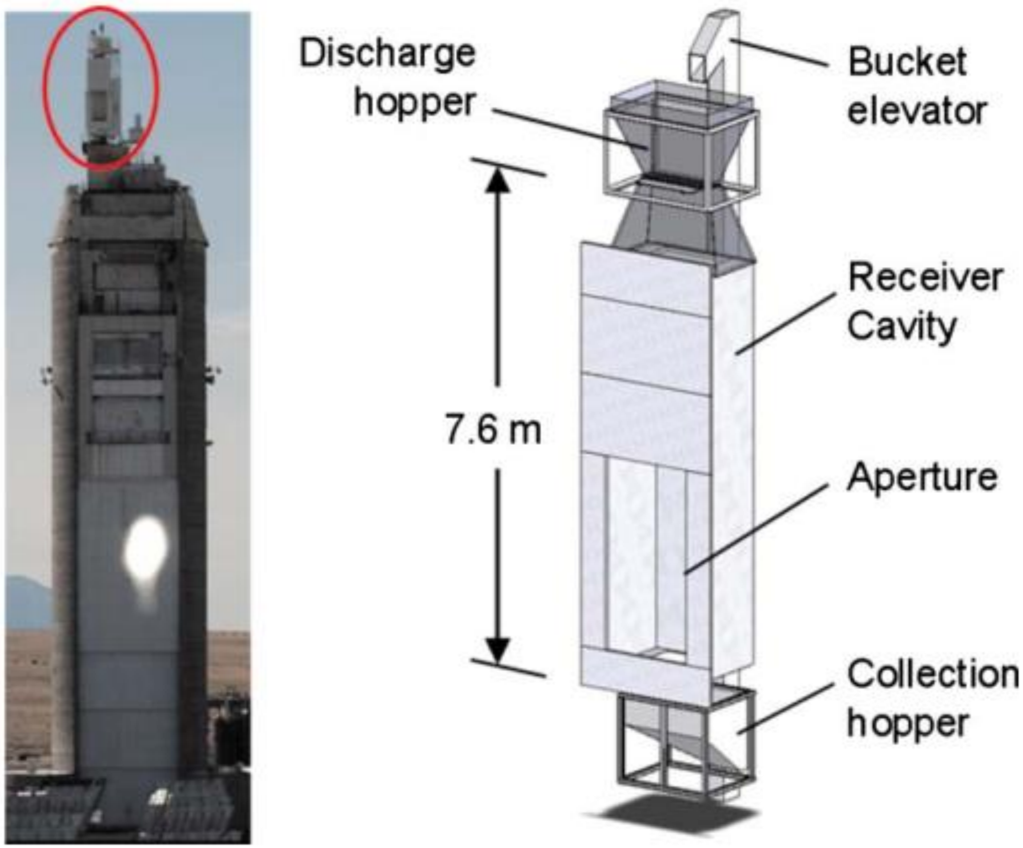
APSRC

Introduction



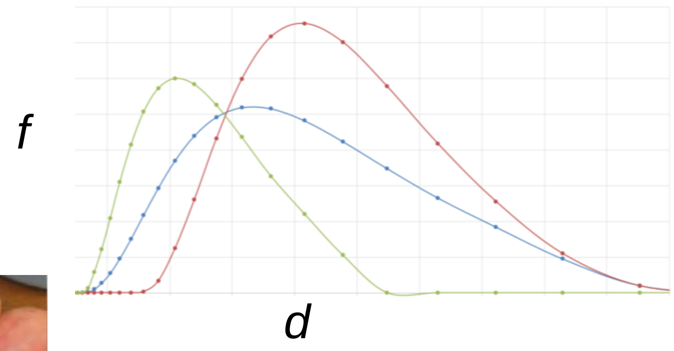
Free-falling particle curtain

Free-falling particle receiver

Nathan P. Siegel et al., *Journal of solar energy engineering*, 2010

Objective

Uniform particles are used in the studies for radiative transfer calculation

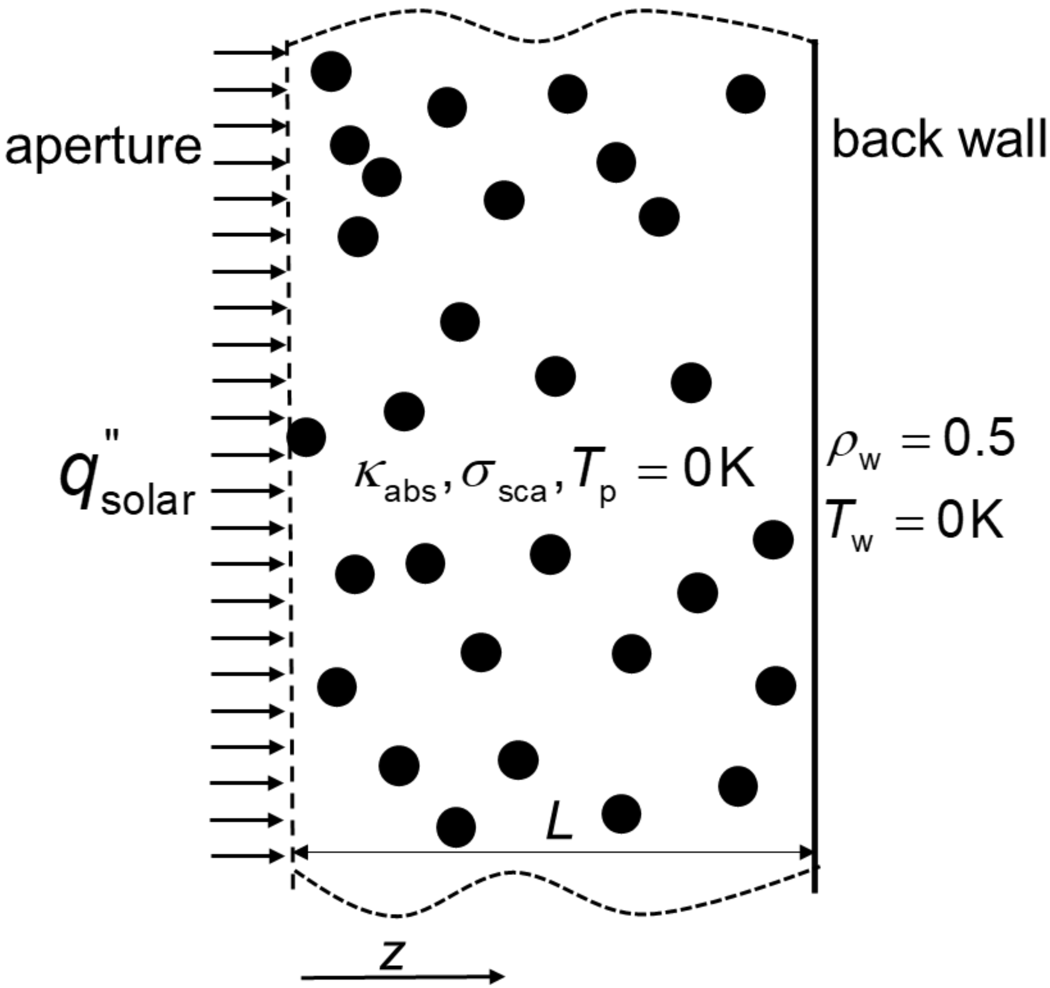


non-uniform CARBO HSP particles

Particle size distribution effect on radiative heat transfer ???

Problem statement

A simplified curtain : 1D model containing suspension of particles



$$f(a) = \lim_{\Delta a \to 0} \frac{V(a)}{V_{tot}\Delta a} = \lim_{\Delta a \to 0} \frac{\tilde{f}(a)}{\Delta a}$$

$$n(a) == \lim_{\Delta a \to 0} \frac{N(a)}{V_{cell}\Delta a}$$

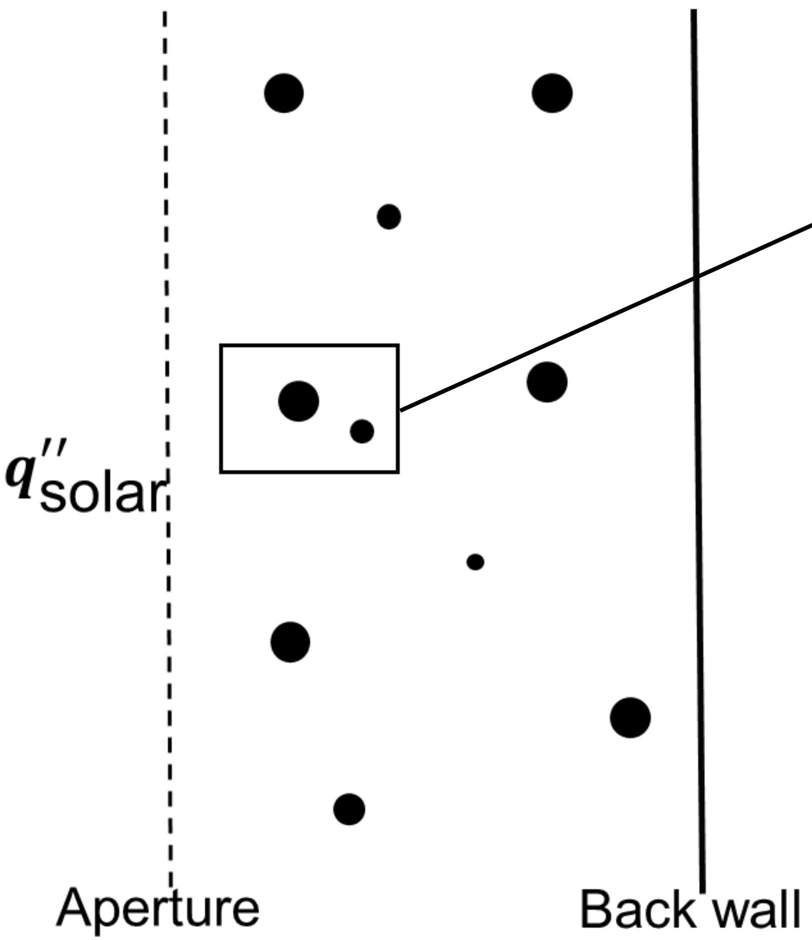
$$n(a) = f(a)\frac{f_v}{\frac{4}{3}\pi a^3}$$

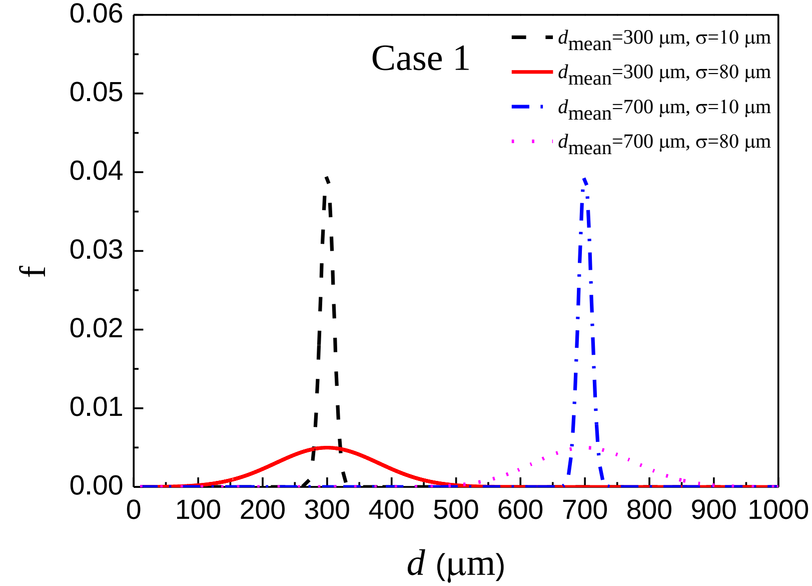
$f(a)$: continuous volume frequency function
$n(a)$: particle size distribution
f_v: volume fraction

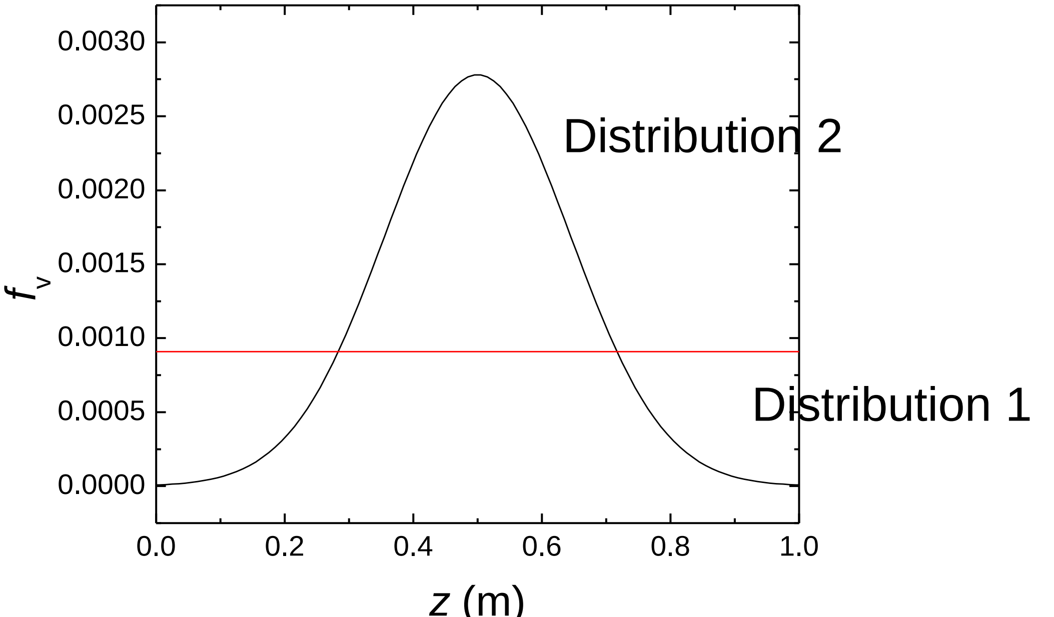
Gaussian distribution

$$f(a) = c\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(a-a_{mean})^2}{2\sigma^2}}$$

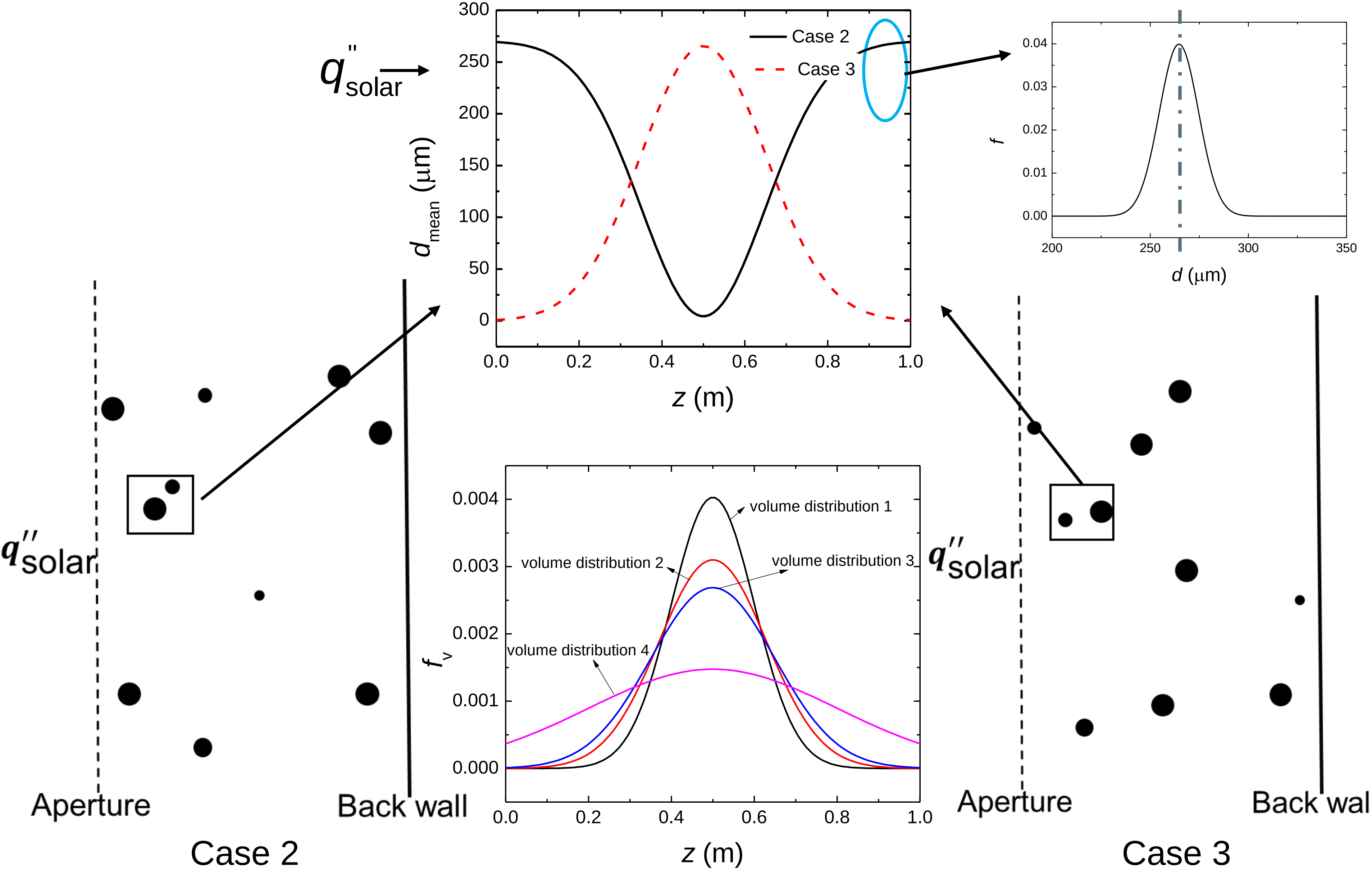
Particle curtain configurations







Particle curtain configurations



The radiative transfer (RTE) equation

$$\frac{\mathrm{d}I}{\mathrm{d}x} = \kappa I_\mathrm{b} - \beta I + \frac{\sigma_\mathrm{s}}{4\pi}\int_{4\pi} I(\hat{\boldsymbol{s}}_i)\Phi(\hat{\boldsymbol{s}}_i, \hat{\boldsymbol{s}})\mathrm{d}\Omega_i$$

The radiative heat flux

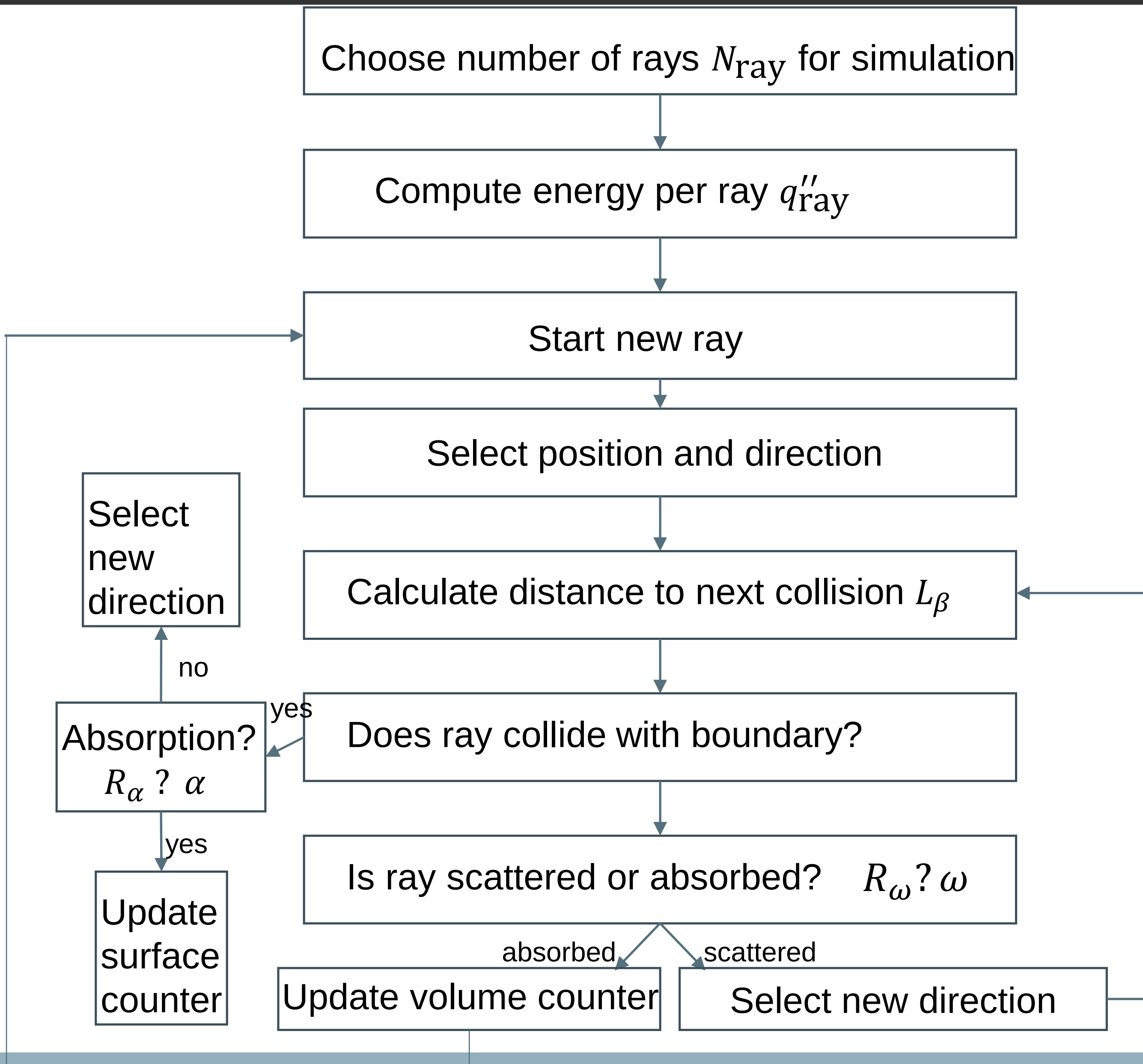
$$\nabla \cdot \boldsymbol{q}'' = \int_{4\pi} \frac{\mathrm{d}I}{\mathrm{d}s}\mathrm{d}\Omega = \kappa(4\pi I_\mathrm{b} - G), \qquad G = \int_{4\pi} I\mathrm{d}\Omega$$

Boundary condition

$$s = 0, \hat{\boldsymbol{s}} \cdot \hat{\boldsymbol{n}} > 0 : I(s, \hat{\boldsymbol{s}}) = I_\mathrm{solar} = \frac{2q''_\mathrm{solar}}{\pi(1 - \cos 2\theta_\mathrm{max})}$$

$$s = 1, \hat{\boldsymbol{s}} \cdot \hat{\boldsymbol{n}} < 0 : I(s, -\hat{\boldsymbol{s}}) = I(s) = \frac{\rho_\mathrm{bw} I(s, \hat{\boldsymbol{s}}_i)}{\pi}$$

MCRT



Validation: M. A. Heaslet et al., *International Journal of Heat and Mass Transfer*,1965.

Radiative properties

Absorption coefficient

$$\kappa_{\text{abs}} = \int_0^\infty \pi Q_{\text{abs}} a^2 n(a)\text{d}a = 3\int_0^\infty Q_{\text{abs}} \frac{f(a)}{4a} f_{\text{v}} \text{d}a$$

Scattering coefficient

$$\sigma_{\text{sca}} = \int_0^\infty \pi Q_{\text{sca}} a^2 n(a)\text{d}a = 3\int_0^\infty Q_{\text{sca}} \frac{f(a)}{4a} f_{\text{v}} \text{d}a$$

Extinction coefficient

$$\beta_{\text{ext}} = \int_0^\infty \pi Q_{\text{ext}} a^2 n(a)\text{d}a = 3\int_0^\infty Q_{\text{ext}} \frac{f(a)}{4a} f_{\text{v}} \text{d}a$$

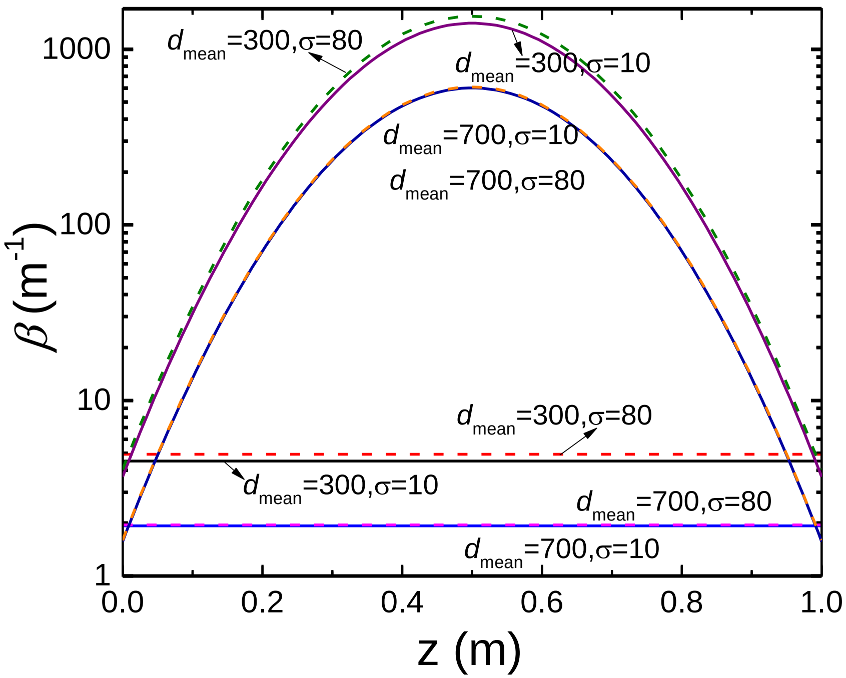
Phase function

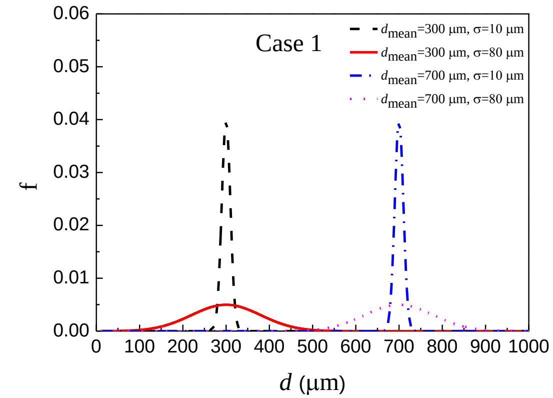
$$\Phi_T = \frac{\int_0^\infty \pi Q_{\text{sca}} \Phi(a,\Theta) a^2 n(a)\text{d}a}{\int_0^\infty \pi Q_{\text{sca}} a^2 n(a)\text{d}a} = \frac{\int_0^\infty Q_{\text{sca}} \Phi(a,\Theta) f(a) f_v \text{d}a}{\int_0^\infty Q_{\text{sca}} f(a) f_v \text{d}a}$$

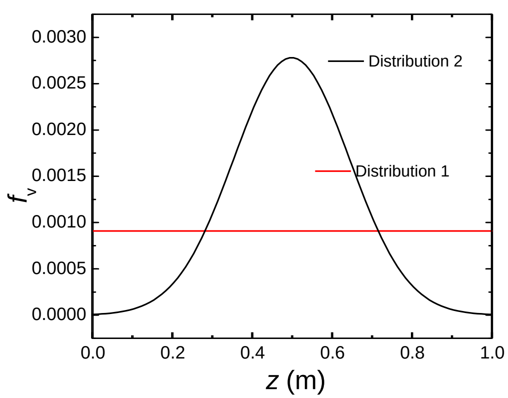
where, Q_{abs}, Q_{sca}, Q_{ext} are the absorption, scattering and extinction factor respectively, obtained from Lorenz—Mie theory.

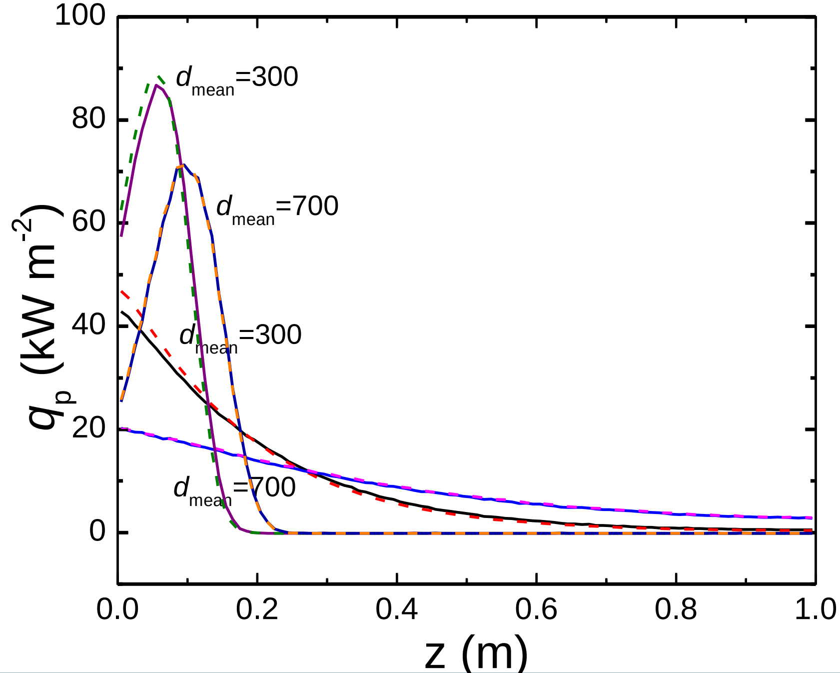
Large particles: geometric optics $Q_{\text{ext}} = 1$, $Q_{\text{sca}} = \rho$

Case 1

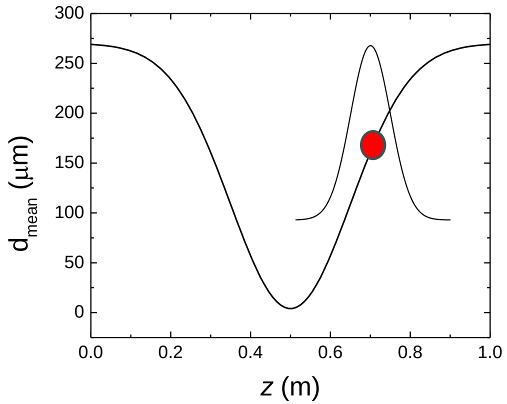

1000
100
10
1
β (m-1)
0.0
0.2
0.4
0.6
0.8
1.0
z (m)
dmean=300,σ=80
dmean=300,σ=10
dmean=700,σ=10
dmean=700,σ=80
dmean=300,σ=80
dmean=300,σ=10
dmean=700,σ=80
dmean=700,σ=10


Case 1
dmean=300 μm, σ=10 μm
dmean=300 μm, σ=80 μm
dmean=700 μm, σ=10 μm
dmean=700 μm, σ=80 μm
f
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0
100
200
300
400
500
600
700
800
900
1000
d (μm)

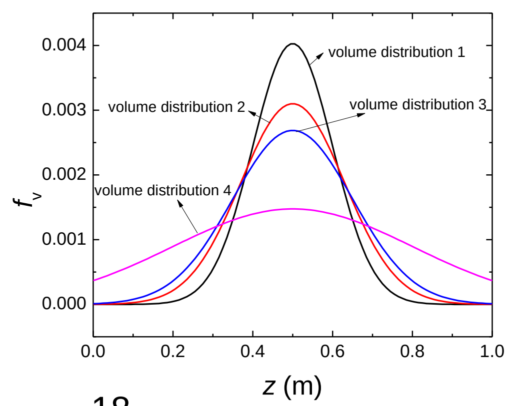

0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
fv
Distribution 2
Distribution 1
0.0
0.2
0.4
0.6
0.8
1.0
z (m)


100
80
60
40
20
0
qp (kW m-2)
dmean=300
dmean=700
dmean=300
dmean=700
0.0
0.2
0.4
0.6
0.8
1.0
z (m)

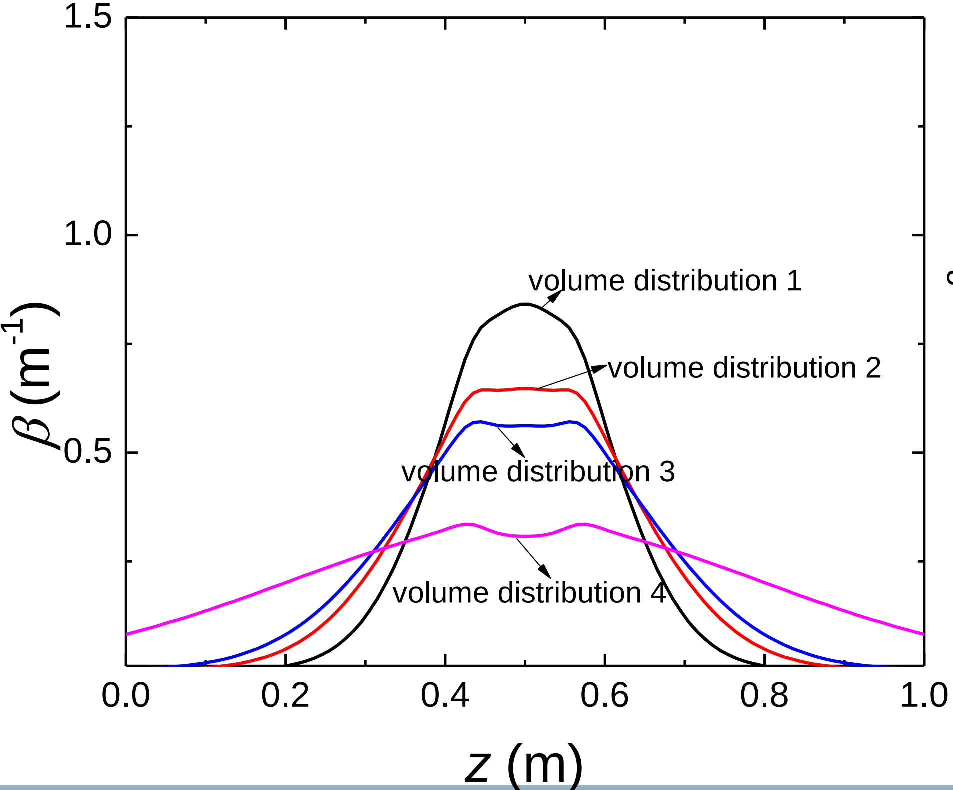
Case 2



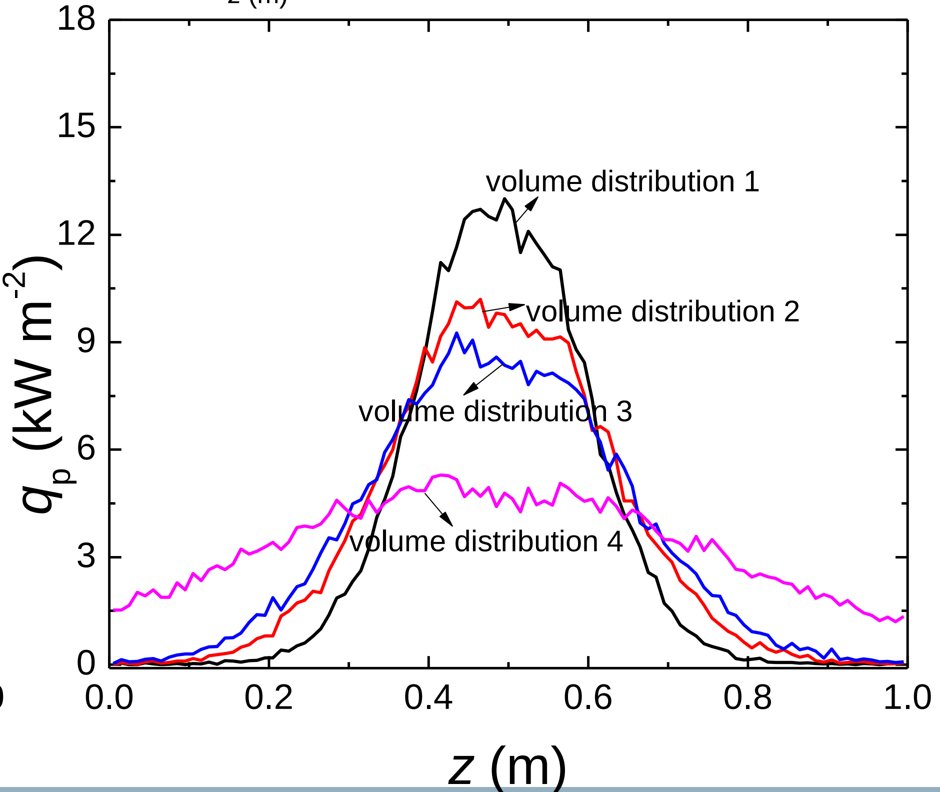
d_mean (μm)
z (m)



volume distribution 1
volume distribution 2
volume distribution 3
volume distribution 4
f_v
z (m)

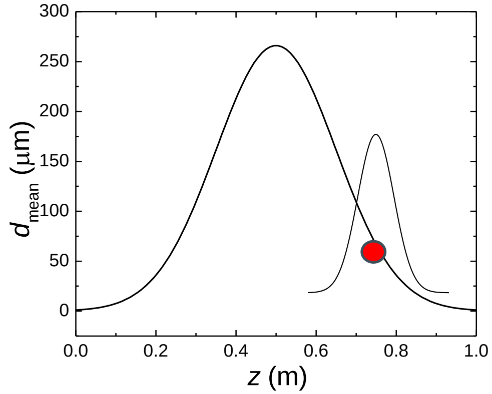


volume distribution 1
volume distribution 2
volume distribution 3
volume distribution 4
β (m-1)
z (m)

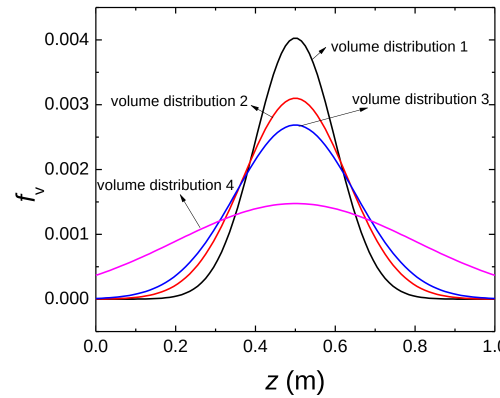


volume distribution 1
volume distribution 2
volume distribution 3
volume distribution 4
q_p (kW m-2)
z (m)

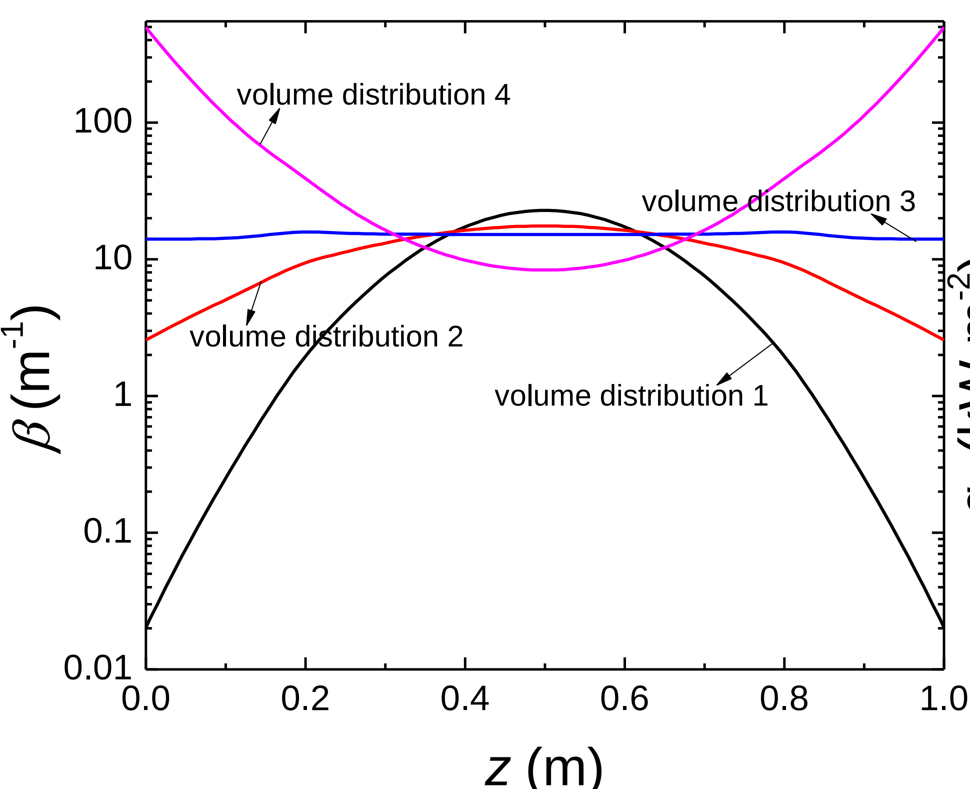
Case 3



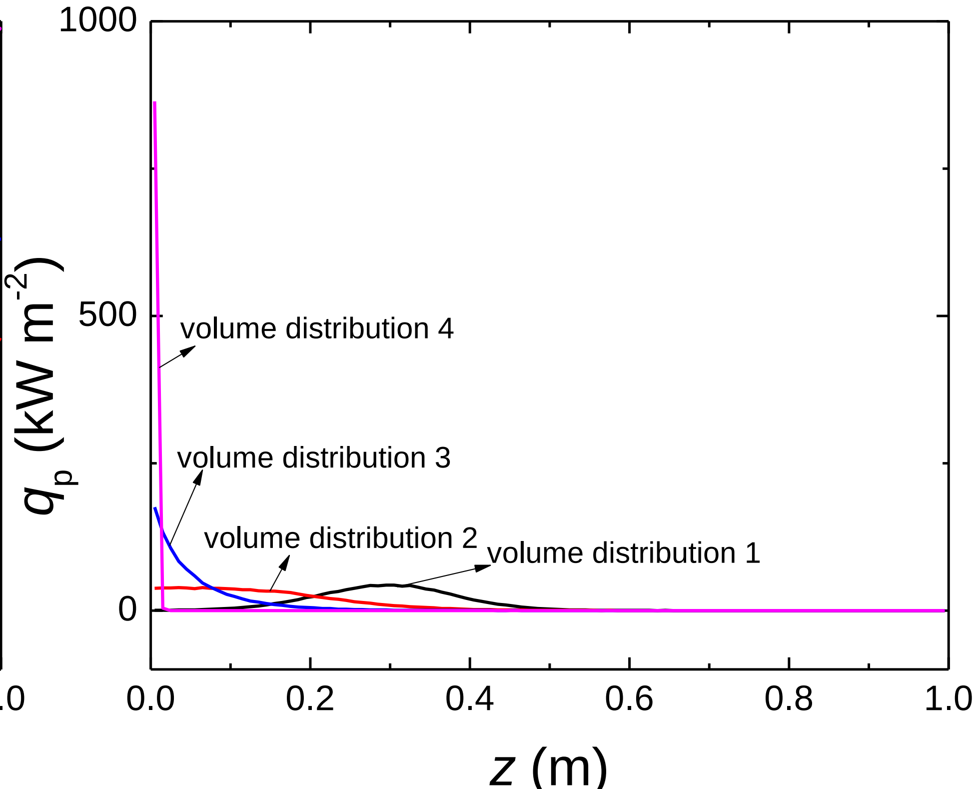
d_{mean} (μm)
300
250
200
150
100
50
0
0.0
0.2
0.4
0.6
0.8
1.0
z (m)



f_v
0.004
0.003
0.002
0.001
0.000
volume distribution 1
volume distribution 2
volume distribution 3
volume distribution 4
0.0
0.2
0.4
0.6
0.8
1.0
z (m)

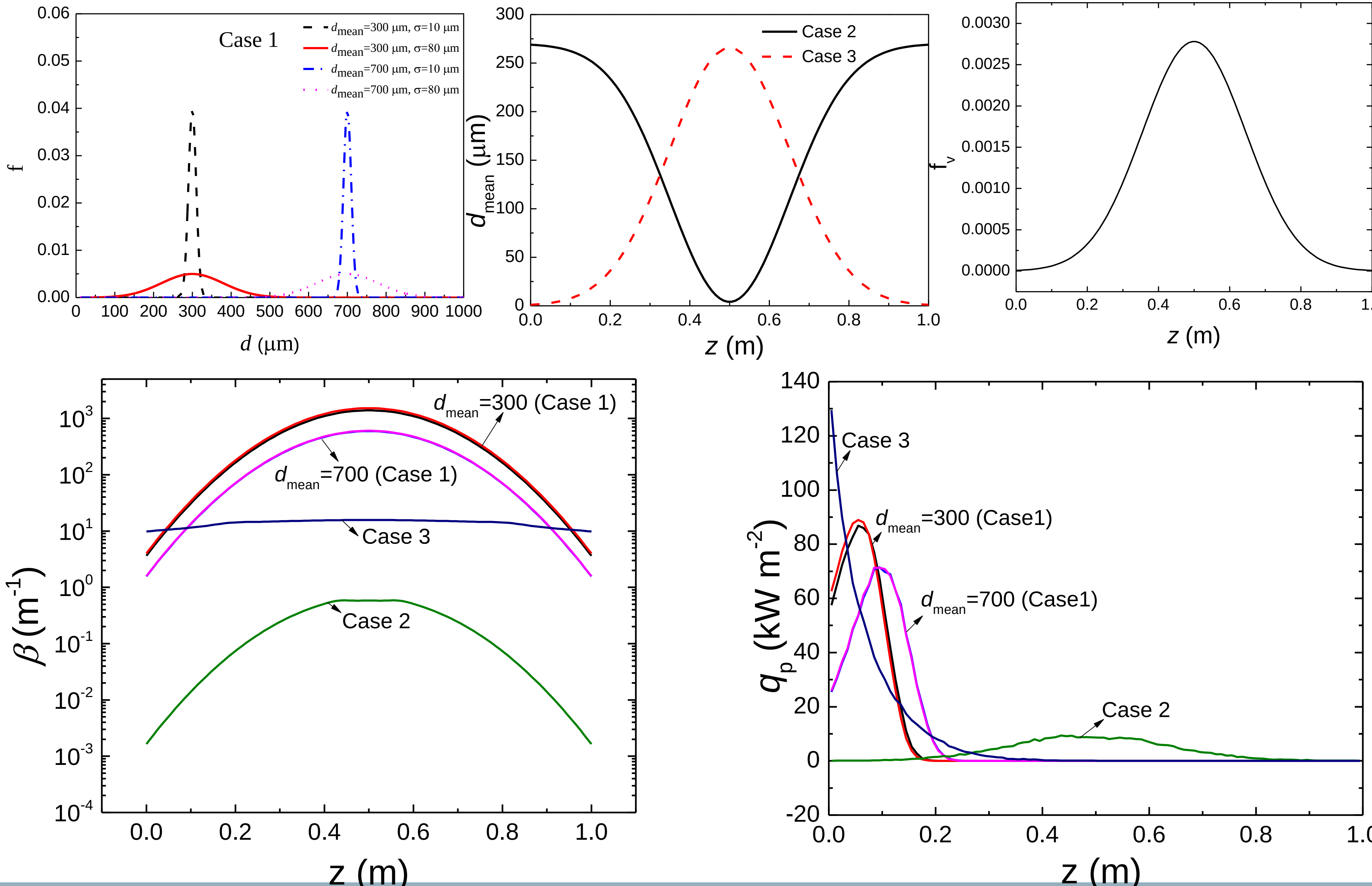


β (m^{-1})
100
10
1
0.1
0.01
volume distribution 4
volume distribution 3
volume distribution 2
volume distribution 1
0.0
0.2
0.4
0.6
0.8
1.0
z (m)



q_p (kW m^{-2})
1000
500
0
volume distribution 4
volume distribution 3
volume distribution 2
volume distribution 1
0.0
0.2
0.4
0.6
0.8
1.0
z (m)

Case 1 & Case 2 & Case 3



Conclusions

- Particles with smaller mean diameter have higher absorption coefficient (same volume fraction). The standard deviation has a small effect on the radiative transfer in the particle curtain.
- The incident energy is attenuated significantly in the front.
- Dust could be a significant factor on performance.
- Small particles with higher volume fraction absorb considerable amount of radiation.
- The radiative power absorption peak can be shifted and designed through controlling the volume fraction distribution.

Australian Government

Australian Renewable Energy Agency

Thanks

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