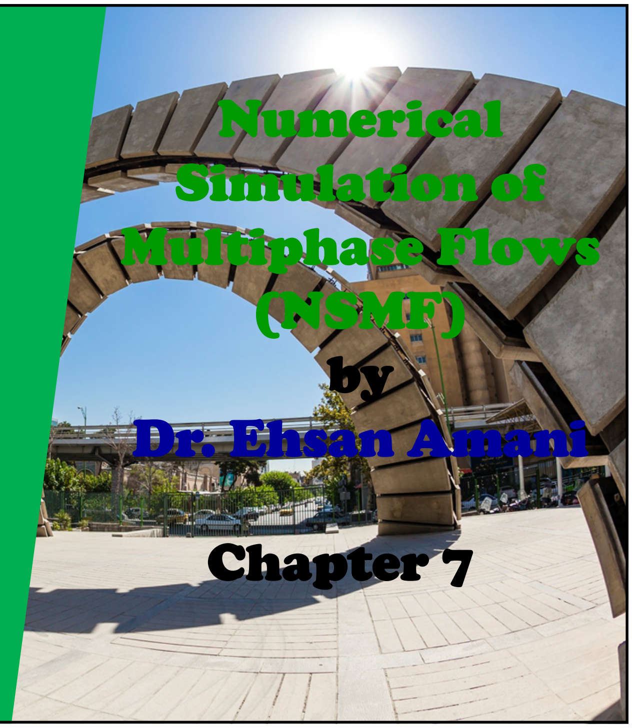


Numerical Simulation of Multiphase Flows (NSMF)

by

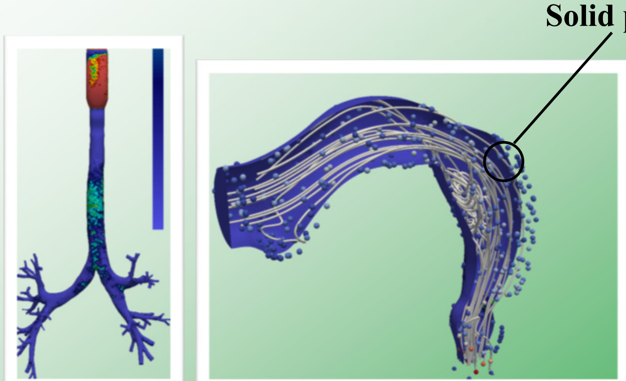
Dr. Ehsan Amani

Chapter 7

Particle

- Particle: solid particle, droplet, or bubble

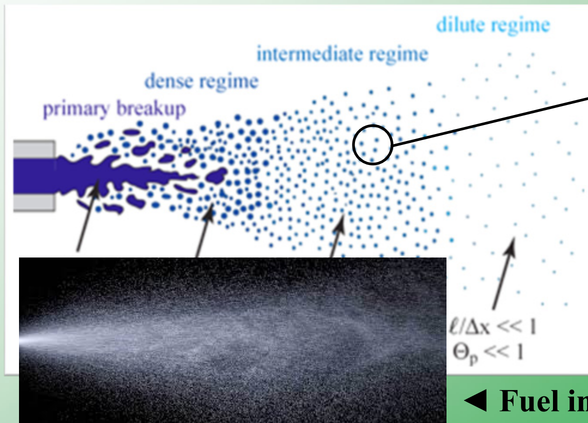
Solid particles



▲ Pulmonary Drug Delivery

Particle

- **Particle: solid particle, droplet, or bubble**



Droplets

◄ Fuel injection in internal combustion engines

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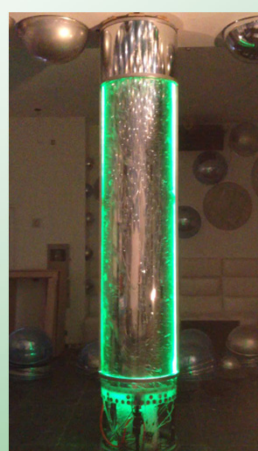
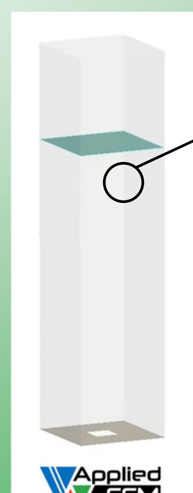
Particle

- **Particle: solid particle, droplet, or bubble**





Bubbles

Bubble column reactor ▲ ►

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Key concepts and definitions

- **Particle concentration and volume fraction**

  ⇨ **Lecture Notes: VII.2**

- **Particle spacing – isolated particle assumption**

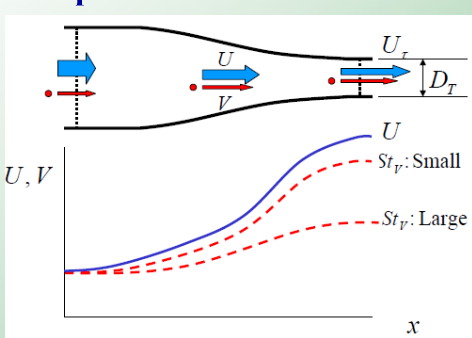
  ⇨ **Lecture Notes: VII.3**

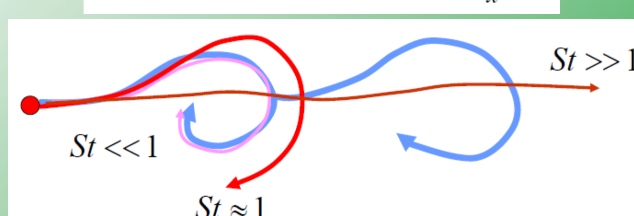
- **Particle time scales – Stokes number**

  ⇨ **Lecture Notes: VII.4**

Stokes number effect

- **Physical interpretation**



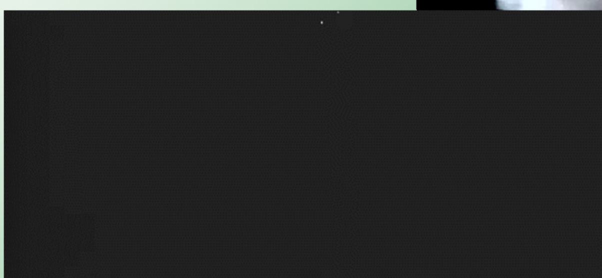


Stokes number effect

- **Application: flow visualization**

Flow past a wing, visualization by smoke particles ►

Convection within a small water droplet ▼



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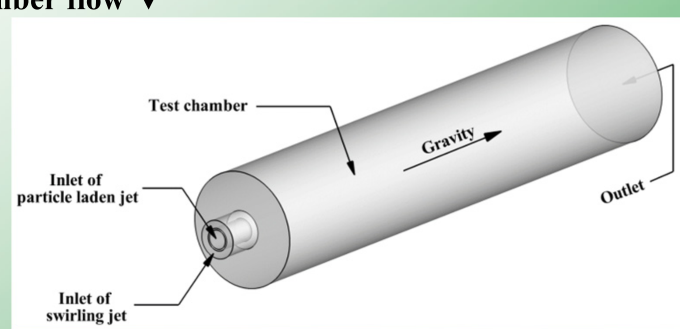
Stokes number effect

- **Application: particle transport**

combustion chamber flow ▼



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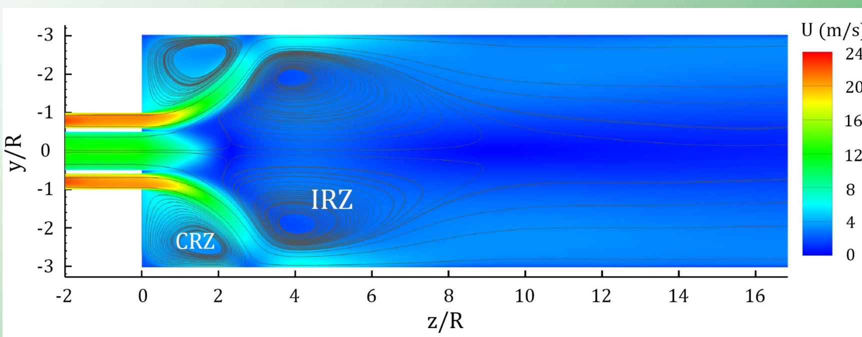
Stokes number effect

- **Application: particle transport**

combustion chamber flow ▼



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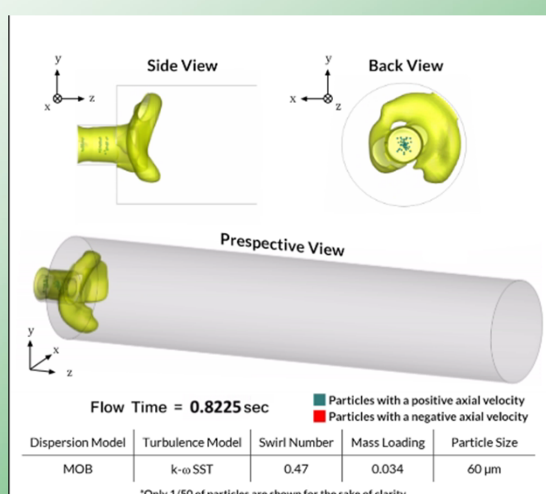
Stokes number effect

- **Application: particle transport**

Particles in a combustion chamber flow ►



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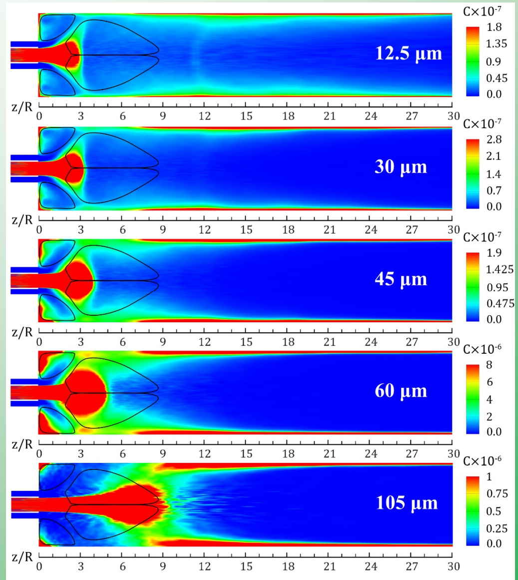
Stokes number effect

Concentration of particles ►



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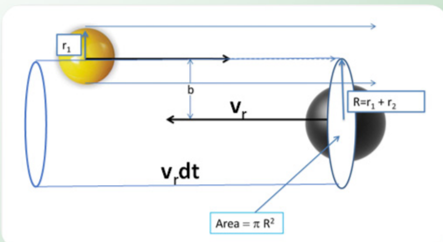
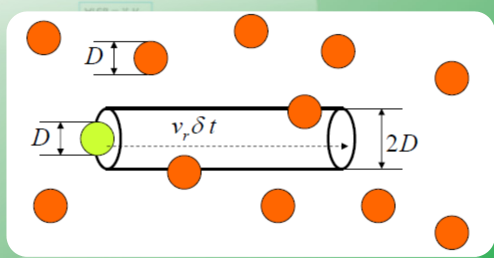
Collision time scale

- The collision cylinder



◄ For two particles

For one particle and a group of particles (in an average sense) ►



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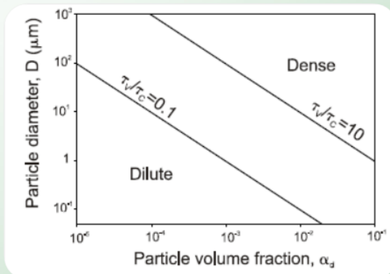
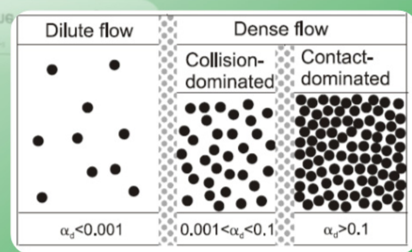
Collision time scale

- **Dilute and dense flow regimes**



◄ **For Glass particles in air with a fluctuating velocity magnitude of 1 m/s**

Only based on the volume fraction value ►



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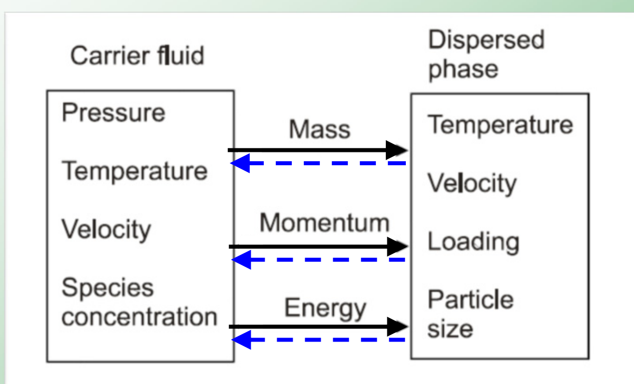
General particle-laden flow regimes

- **Coupling: Fluid-particle interaction**



One-way coupling

Two-way coupling

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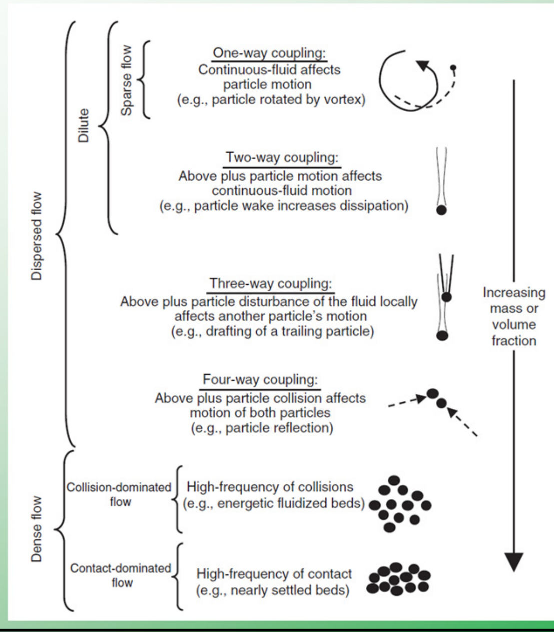
General particle-laden flow regimes



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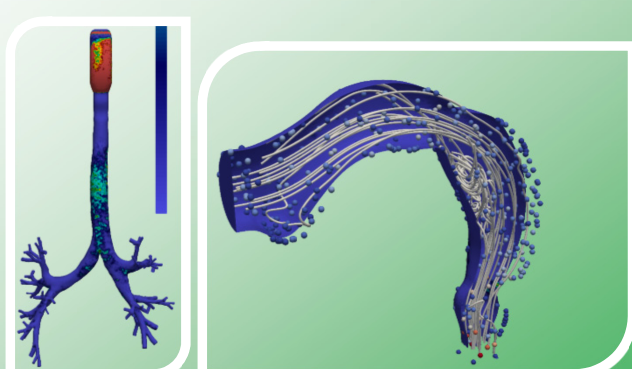
General particle-laden flow regimes

- **One-way coupling regime**



▲ **Pulmonary Drug Delivery** ▲

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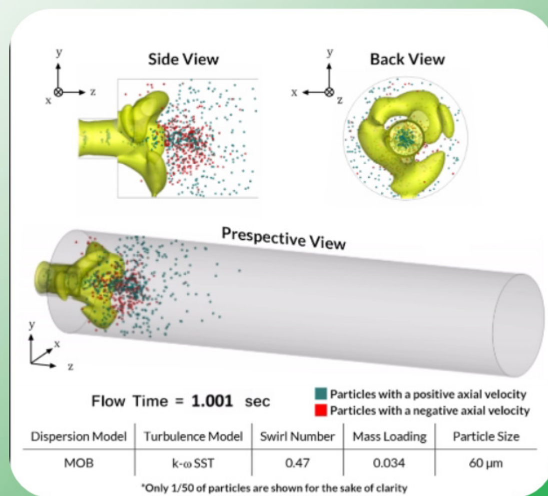
General particle-laden flow regimes

- **Two-way coupling regime**

Particles in a combustion chamber flow ►



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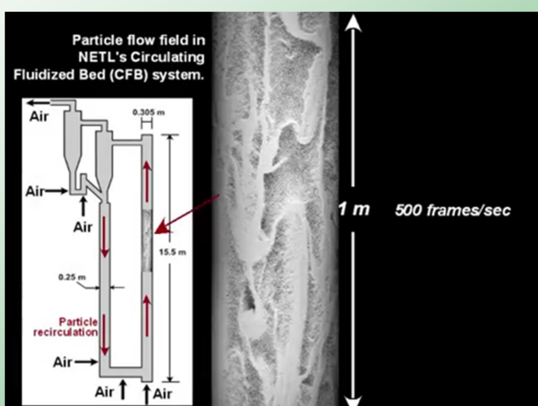
General particle-laden flow regimes

- **Collision-dominated regime**



Energetic fluidized beds ▲

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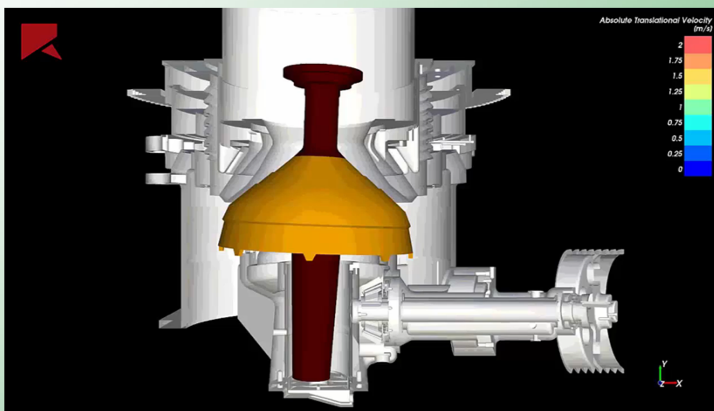
General particle-laden flow regimes

- Contact-dominated regime



Crusher ▲

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Key concepts and definitions

- The coupling

⇨ Lecture Notes: VII.5

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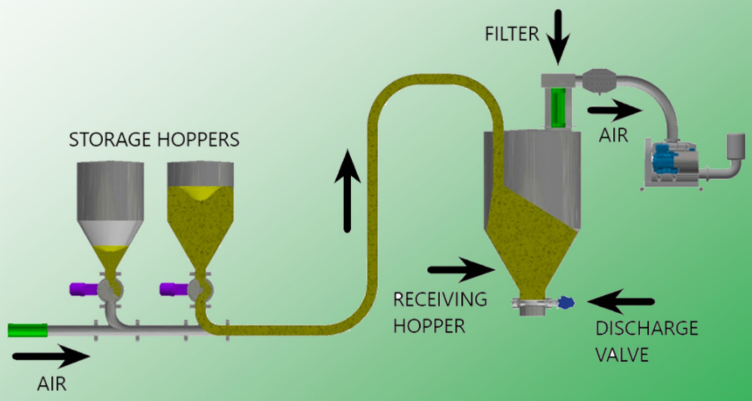
Pneumatic particle transport

- **Modes:**
  - **Dilute-phase pneumatic conveying**



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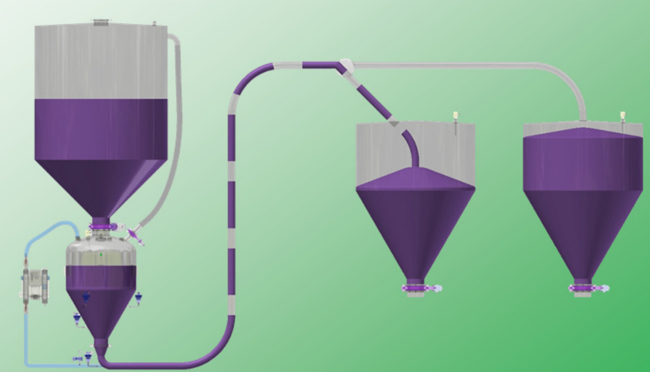
Pneumatic particle transport

- **Modes:**
  - **Dilute-phase pneumatic conveying**
  - **Dense-phase pneumatic conveying**



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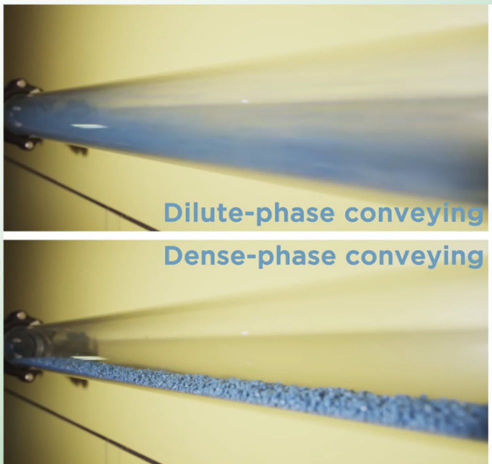
Pneumatic particle transport



Pneumatic particle transport

- **Applications:**
  - **Pharmaceutical industries**

Pneumatic particle transport

- **Applications:**
  - **Pharmaceutical industries**
  - **Mining industries**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Pneumatic particle transport

- **Applications:**
  - **Pharmaceutical industries**
  - **Mining industries**
  - **Agriculture industries**


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Pneumatic particle transport

- Applications:
  - Pharmaceutical industries
  - Mining industries
  - Agriculture industries
  - Tire industries

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Pneumatic particle transport

- Applications:
  - Pharmaceutical industries
  - Mining industries
  - Agriculture industries
  - Tire industries
  - …

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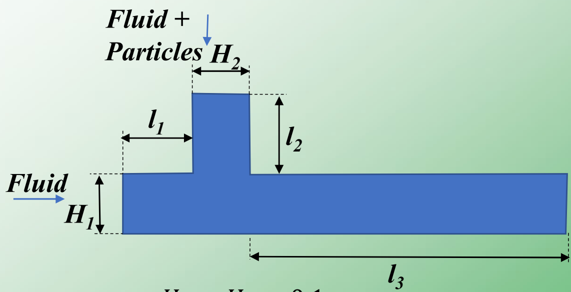
Case study #3: Conveying T-junction

- **Pneumatic conveying T-junction**
  - Problem definition
    1. Geometry



$H_1 = H_2 = 0.1\ m$

$l_1 = l_2 = 0.2\ m$

$l_3 = 1.3\ m$

Depth: $W \to \infty$

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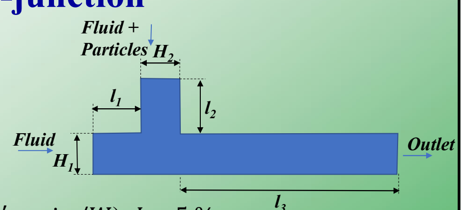
Case study #3: Conveying T-junction

- **Pneumatic conveying T-junction**
  - Problem definition
    1. Geometry
    2. Boundary conditions



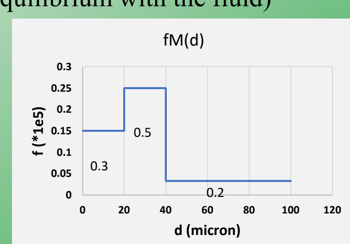
i) Inlets:

(1) Fluid: air $\dot{m}'_a = 0.7 \frac{kg}{s.m}$ $(\dot{m}'_a = \dot{m}_a/W)$, $I = 5\ \%$

(2) Fluid + Particles: air $(\dot{m}'_a = 0.7\ \frac{kg}{s.m}, I = 5\ \%)$, Sand Particles $(\dot{m}'_p = 0.07, 0.7\ \frac{kg}{s.m}$, in equilibrium with the fluid)

ii) Walls

iii) Outlets



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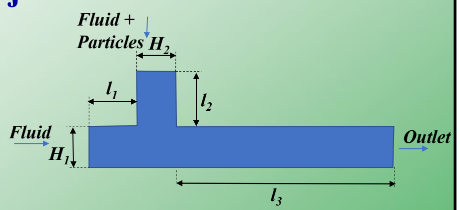
Case study #3: Conveying T-junction

- **Pneumatic conveying T-junction**
  - Problem definition
    1. Geometry
    2. Boundary conditions
    3. Material properties



$\rho_{air} = 1.225\frac{kg}{m^3}$, $\mu_{air} = 1.8 \times 10^{-5}\ Pa.s$

$\rho_p = 1500\frac{kg}{m^3}$

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Case study #3: Conveying T-junction

- **Pneumatic conveying T-junction**
  - Eulerian-Lagrangian simulation
    1. Preliminary analysis
    2. Solution using ANSYS Fluent (Chap 9)

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Case study #3: Conveying T-junction

- **Preliminary analysis**

$\alpha_p = ?$

HW#7: $\alpha_p = \frac{c}{b}$, $c = \frac{\dot{m}_p''}{\rho_p}, b = \left(\frac{\dot{m}_c''}{\rho_c} + \frac{\dot{m}_p''}{\rho_p}\right)$

$\dot{m}_c'' = \frac{0.7}{0.1} = 7\ \frac{kg}{m^2 s}$, $\dot{m}_p'' = \frac{0.07}{0.1} = 0.7\ \frac{kg}{m^2 s} \rightarrow \alpha_p = 8.16 \times 10^{-5}, \alpha_c = 1 - \alpha_p = 0.999918$

Continuous-phase flow regime (laminar vs. turbulent)?

$Re_{D_H} = \frac{\rho_c \tilde{u}_c D_H}{\mu_c}, D_H = \lim_{W\to\infty}\left(\frac{4WH_1}{2H_1+2W}\right) = 2H_1 = 0.2\ m$

$\dot{m}_c'' = \bar{\rho}_c \tilde{u}_c$, $\bar{\rho}_c = \alpha_c \rho_c = 1.224\ \frac{kg}{m^3} \rightarrow \tilde{u}_c = 5.72\frac{m}{s} \rightarrow Re_{D_H} = 77841$ (Fully turbulent)

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Case study #3: Conveying T-junction

- **Preliminary analysis**

Maximum number of particles in the computational domain (Depth=1m)?

$N_{p,tot} = n_p \forall_p$

$\forall_p \sim 0.1 \times 1.6 \times 1 = 0.16\ m^3$

$n_p = \frac{\bar{\rho}_p}{m_p}$, $m_p = \frac{\pi}{6}\rho_p d_p^3$, $(d_p = 30\ \mu m) \rightarrow m_p = 2.12 \times 10^{-13}\ kg$, $\bar{\rho}_p = \alpha_p \rho_p = 0.1224\ \frac{kg}{m^3}$

$\rightarrow n_p = 5.77 \times 10^{11}\ \frac{particles}{m^3} \rightarrow N_{p,tot} = 9.23 \times 10^{10}\ particles$

Loading?

$c = z = \frac{\bar{\rho}_p}{\bar{\rho}_c} = 0.1,\ Z = \frac{\dot{m}_p}{\dot{m}_c} = 0.1$

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Case study #3: Conveying T-junction

- **Preliminary analysis**

Isolated particles?

$\frac{l}{d} = \left(\frac{\pi}{6\alpha_p}\right)^{1/3} = 18.58 \; ?> 10$ (Isolated particles)

Stokes number?

$\tau_F \sim \frac{H_1}{\tilde{u}_c} = 0.0175\, s$

$\tau_v \sim \frac{\rho_p d_p^2}{18\mu_c}, \; (d_p = 30\, \mu m) \rightarrow \; \tau_v = 4.167\, ms$

$St_v = \frac{\tau_v}{\tau_F} = 0.238 \; ? \ll 1$ (Particles are not tracer)

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Case study #3: Conveying T-junction

- **Preliminary analysis**

Dense vs. dilute (collision modeling)?

$\tau_c \sim \frac{\sqrt{\pi}}{4n_p d_p^2 u'}, \; (d_p = 30\, \mu m), u' = \frac{I}{100}\tilde{u}_c = 0.286 \rightarrow \; \tau_c = 2.98\, ms$

$\frac{\tau_v}{\tau_c} \sim 1.398 \; ?< 10$ (Collisions may be unimportant)

One-way vs. two-way coupling?

$\Pi_v = \frac{c}{1+St_v} = 0.081 \; ? \ll 1$ (Two-way coupling is probably unimportant)

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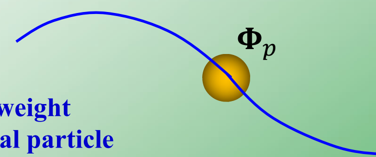
The point-particle assumption

- **Particle state vector**



Parcel weight
$w_p = 1$ **: real particle**

$$\boldsymbol{\Phi}_p \equiv (\overbrace{\boldsymbol{x}_p, \boldsymbol{u}_p, d_p, T_p, \dots}^{\text{Particle primary properties}}, \underbrace{\boldsymbol{u}_s, T_s, \dots}_{\text{fluid properties seen by particle}}, w_p) \qquad (41.7)$$

- **Parcel (Computational particle) vs. real particle**

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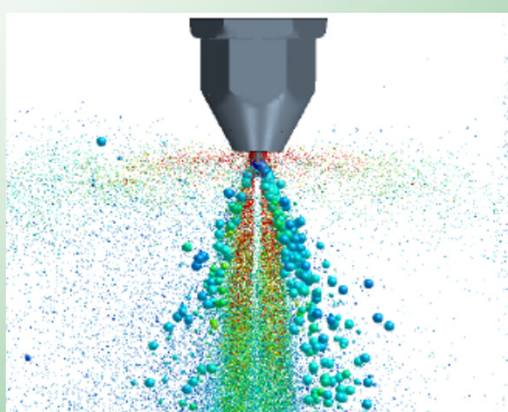
The size distribution

- **Post-processing**



Water spray ▲

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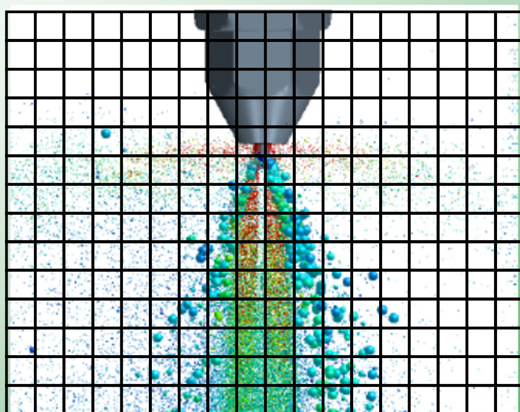
The size distribution

- **Post-processing**



Water spray ▲

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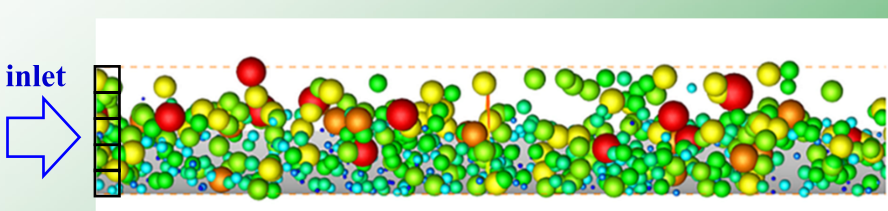
The size distribution

- **Setting boundary conditions**



Gas-solid flow in a duct▲

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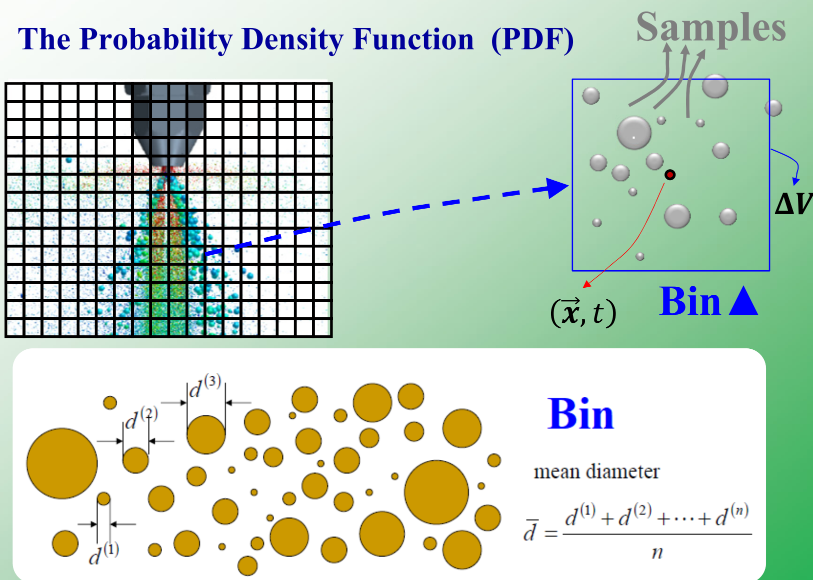
The size distribution

- **The Probability Density Function (PDF)**



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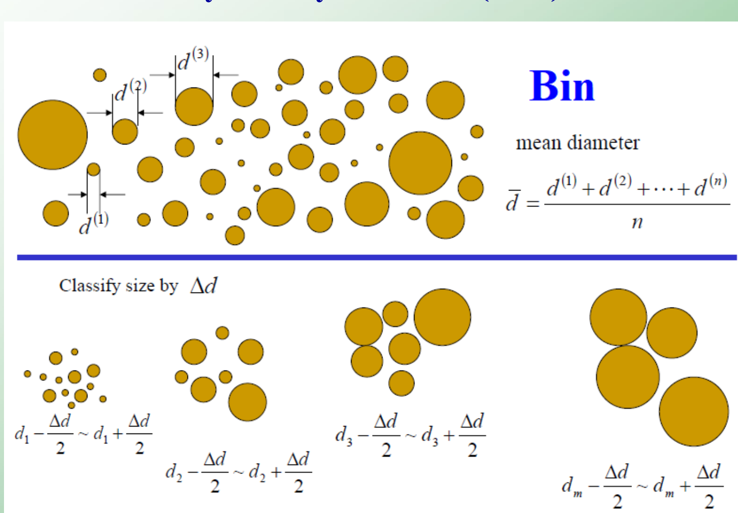
The size distribution

- **The Probability Density Function (PDF)**



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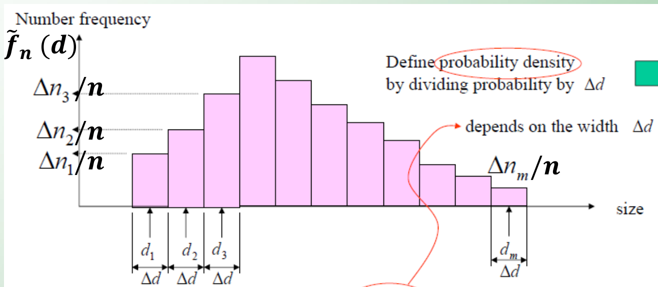
The size distribution

- **The Probability Density Function (PDF)**



$$\bar{d} = \frac{d^{(1)} + d^{(2)} + \cdots + d^{(n)}}{n}$$

Probability : size takes $d_1 - \frac{\Delta d}{2} \sim d_1 + \frac{\Delta d}{2}$

" $d_2 - \frac{\Delta d}{2} \sim d_2 + \frac{\Delta d}{2}$

$$\bar{d} = \frac{d_1 \cdot \Delta n_1 + d_2 \cdot \Delta n_2 + \cdots + d_m \cdot \Delta n_m}{n}$$

" $d_3 - \frac{\Delta d}{2} \sim d_3 + \frac{\Delta d}{2}$

$$\bar{d} = d_1 \cdot \frac{\Delta n_1}{n} + d_2 \cdot \frac{\Delta n_2}{n} + d_3 \cdot \frac{\Delta n_3}{n} + \cdots d_m \cdot \frac{\Delta n_m}{n}$$

" $d_m - \frac{\Delta d}{2} \sim d_m + \frac{\Delta d}{2}$

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The size distribution

- **The Probability Density Function (PDF)**

$\boxed{\frac{\Delta n_1}{n \cdot \Delta d} = f(d_1)}$ $\boxed{\frac{\Delta n_2}{n \cdot \Delta d} = f(d_2)}$ $\boxed{\frac{\Delta n_3}{n \cdot \Delta d} = f(d_3)}$ $\cdots$ $\boxed{\frac{\Delta n_m}{n \cdot \Delta d} = f(d_m)}$

$$\bar{d} = d_1 \cdot \frac{\Delta n_1}{n} + d_2 \cdot \frac{\Delta n_2}{n} + d_3 \cdot \frac{\Delta n_3}{n} + \cdots d_m \cdot \frac{\Delta n_m}{n} \qquad \frac{\Delta n}{n} = f(d)\Delta d$$

$$\bar{d} = d_1 \cdot f(d_1) \cdot \Delta d + d_2 \cdot f(d_2) \cdot \Delta d + d_3 \cdot f(d_3) \cdot \Delta d + \cdots d_m \cdot f(d_m) \cdot \Delta d$$

limit $m \to \infty$

$$\bar{d} = \lim_{m \to \infty} \sum_{i=1}^{m} d_i \cdot f(d_i) \cdot \Delta d = \int_0^\infty d \cdot f(d) \cdot \mathrm{d}d$$

probability density

probability density function, pdf

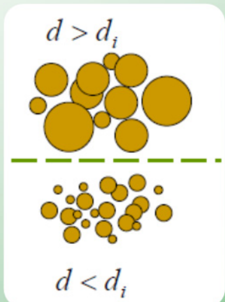
frequency distribution

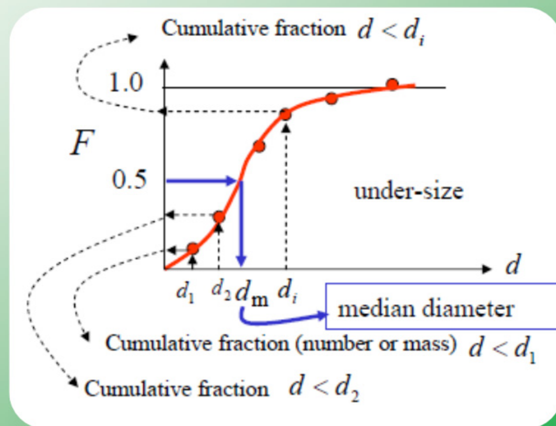
Chap 7 Lecture Notes: VII.9 By E. Amani

The size distribution

- **The Cumulative Distribution Function (CDF)**

$$F=\int_0^d f(d)\cdot \mathrm{d}d$$





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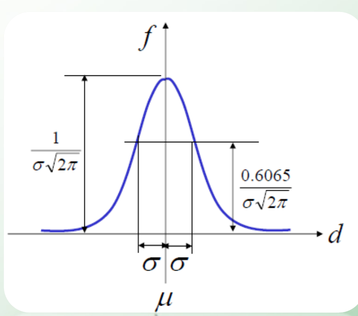
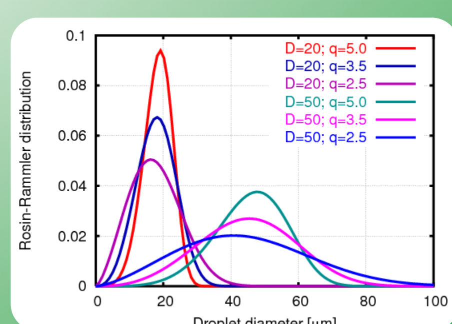
Analytical distribution functions



◄ **The normal distribution**

The Rosin-Rammler distribution ►



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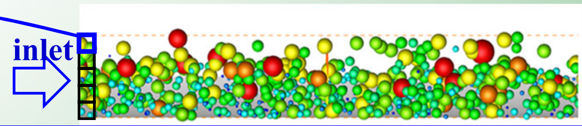
Sample problem



For a particle-laden flow, the size distribution PDF of particles at the injection location is given by the following so-called "exponential distribution":

$$f(d)=\begin{cases}\lambda e^{-\lambda d} & ;d\geq 0\\ 0 & ;d<0\end{cases}$$

where $\lambda = 2.5\times 10^{4}\, m^{-1}$.

Lecture Notes: VII.10

Hint: $\int xe^{cx}dx = -\frac{e^{cx}}{c^2}+\frac{xe^{cx}}{c}$, $\int_0^\infty x^n e^{-ax}dx = \frac{n!}{a^{n+1}}$ $(a>0, n=0,1,2,\dots)$

a) What is the particle mean diameter?
b) 95% of particles have a diameter smaller than $d_{95\%}$. What is $d_{95\%}$?
c) Obtain the mas-based PDF, $f_M(d)$?
d) D is the diameter that particles with $d_p > D$ contain only 5% of the total mass. Is D smaller, equal, or greater than $d_{95\%}$ obtained in part (b)?

Hands-on practice

- **HW#7:**
  - **A sample preliminary EL analysis**
  - **Working with size distributions**
  - **…**

Size range (μm)	Number of particles	Size range (μm)	Number of particles
5-15	56	40-45	41
15-20	62	45-50	38
20-25	73	50-60	38
25-30	79	60-70	21
30-35	58	70-80	12
35-40	39	80-95	15