Numerical simulation of solid particle deposition in ducts

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Particle deposition

- Solid particles suspended in gas or liquid flows tend to *settle* down more or less quickly depending on *relative density* and *particle Reynolds number*. The main mechanism here is *gravity*.
- Particles also may exhibit *adhesion* to the surfaces. Here the main mechanism are the *Van der Waals forces*.
- *Deposition by gravity* is comparatively more important for *large particles*.
- Conversely *adhesion* is more important for *small particles*.
- Particle deposition in ducts is generally bad, because
  - ▷ Increases friction and then *pressure drop* along the duct.
  - ▷ Promotes *corrosion*.
  - ▷ Increases the *weight load* to the structure. This is important for *very large ducts*.

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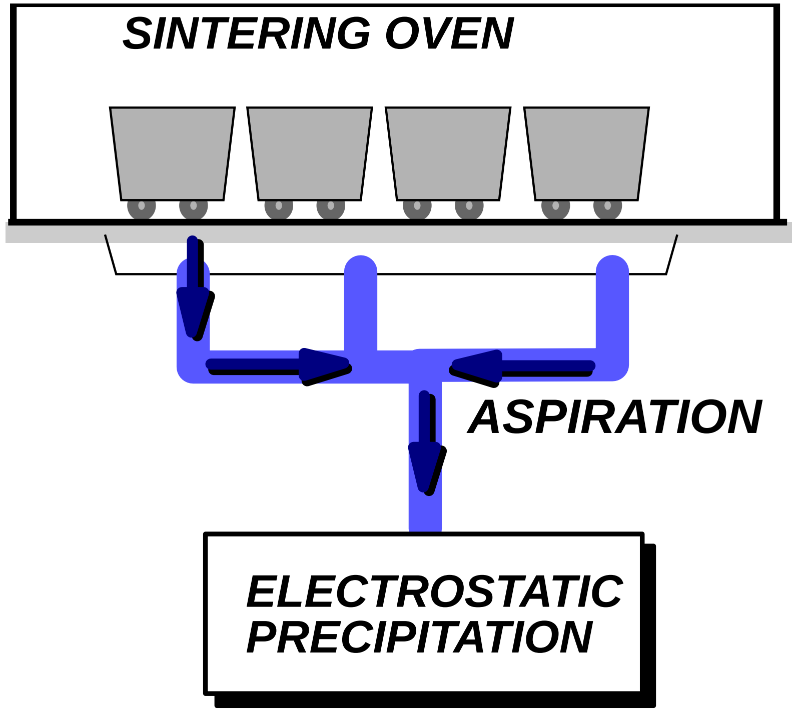
Particle deposition in ducts. Industrial problem.

- Case studied is a *ventilation duct* in a *sintering facility* for a large steel making plant.
- Medium size pellets are produced from iron mineral small particles in a large oven by *sintering*.
- A certain amount of particles are captured by the aspiration system.
- Due to *environmental regulations* these particles can not be released to the atmosphere. The air/particle mixture is processed in an *electrostatic precipitator*.



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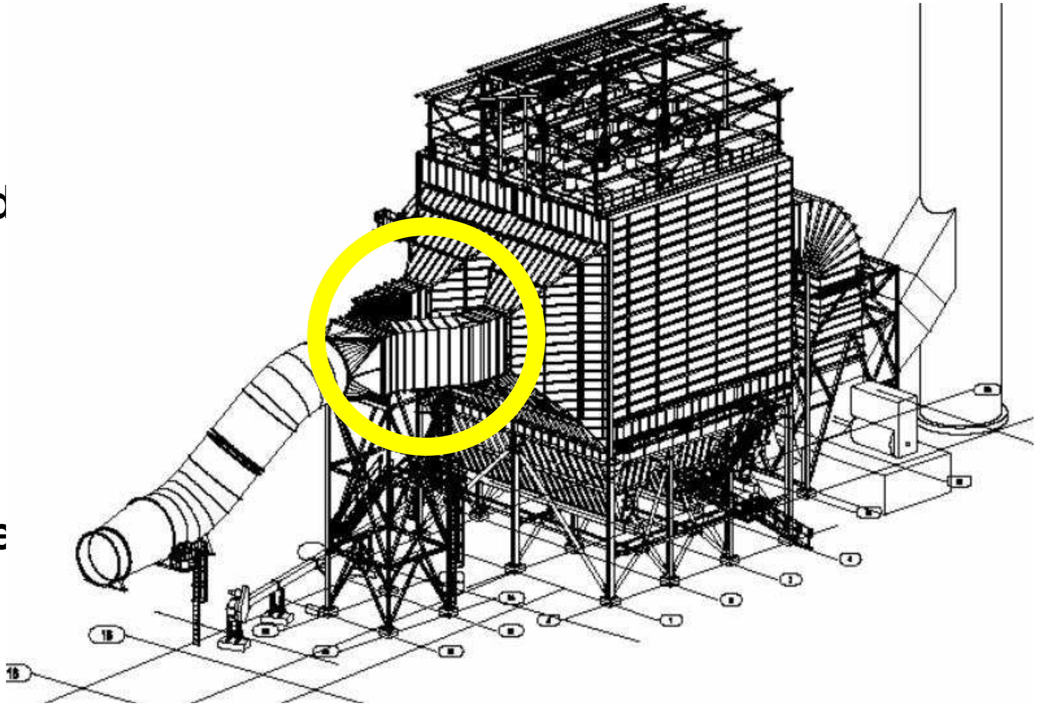
Particle deposition in ducts. The aspiration duct.

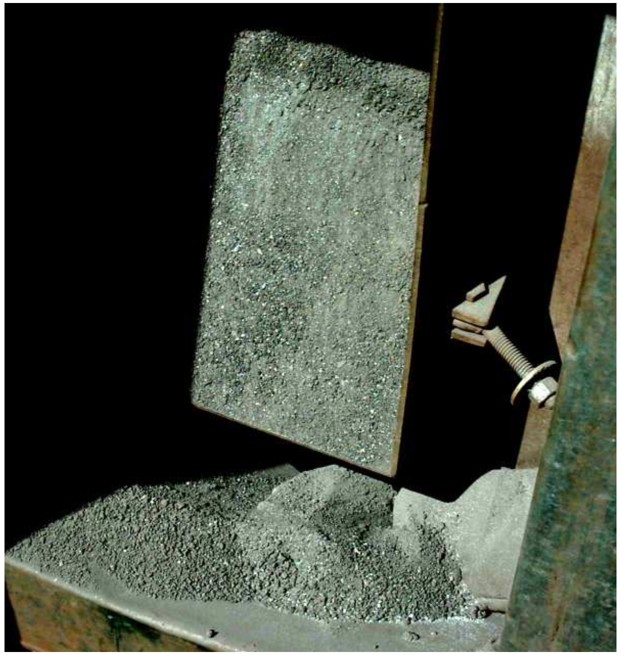
Geometry shows the electrostatic precipitator and the duct. The duct is 3.8m wide in diameter, circular section, 30m long, and ends in two legs that fit into the precipitator.

- **The duct has a S shape. Due to this bends, the are large recirculation areas, and large amounts of material are deposited.**
- **There are many problems with this deposition, mainly it causes a large increase in weight load to the structure.**



Particle deposition in ducts. The aspiration duct. (cont.)

Large deposits of particulated material are found. Depth of material may reach 0.5m. Deposits are formed mainly from large particles (typically 500um or more). Dune like structures are formed by the air stream.



Particle deposition in ducts. The aspiration duct.

Typical operation parameters are:

- **Duct flow rate: 12500 m3/min**
- **Duct speed: 18 m/sec (66 km/h)**
- **Particle apparent density: 1500 kg/m3**
- **Particle fraction in air: 1 g/m3 ($\approx$ 2e4 prtcls/m3, mean distance between particles 3.6cm)**
- ***Total particle mass processed: $Q =$ 18,000 kg/day***

Note the large amount of particulated material that is processed. If the flow conditions are such that the particles tend to deposit at some point of the duct, even a small fraction of them (say 1%), then *large quantities of material will be accumulated*, and the weight load will be significant.

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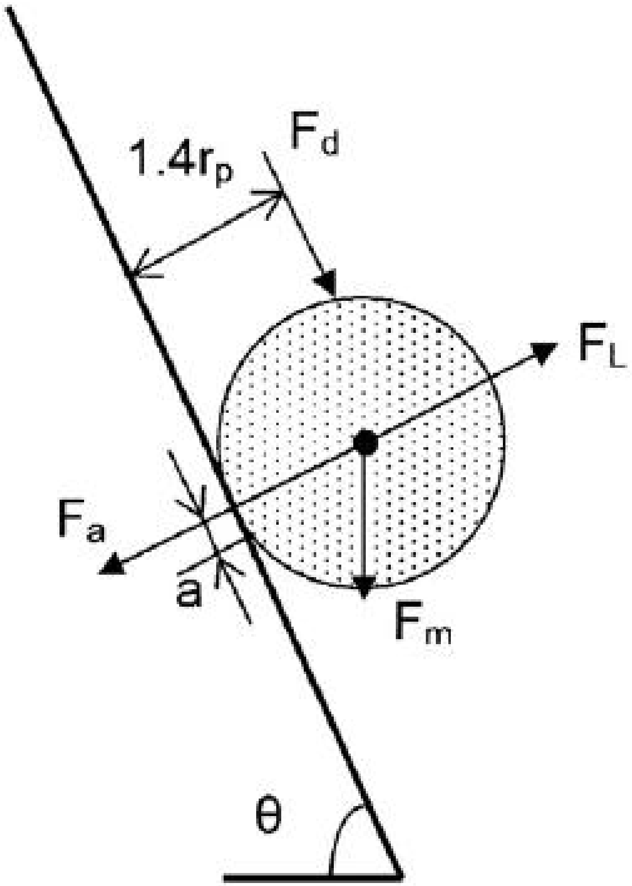
Particle deposition

Forces that act on a particle laying on a solid surface:



- ***Adhesion*: force $\mathbf{F}_a = -{}^3\!/\!_4 \pi \sigma d_p \hat{\mathbf{n}}$ (*Van der Waals*)**
- ***Drag*: $\mathbf{F}_d = 6\pi\mu r_p^2 f\, \boldsymbol{\gamma}$,**
- ***Weight*: $\mathbf{F}_m = -\rho_p g\, {}^4\!/\!_3 \pi r_p^3 \hat{\mathbf{e}}_z$**
- ***Lift*: $\mathbf{F}_l = 9.22(\gamma\mu r_p^2)(\gamma r_p^2/\nu)\, \hat{\mathbf{n}}$.**

where

- **$\sigma =$ *surface energy density* $[\mathrm{J/m^2}]$.**
- **$\boldsymbol{\tau}_w$ *viscous traction* at the wall, $\tau_w = |\boldsymbol{\tau}_w|$**
- **γ *strain rate* tangential to the wall**

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Separation criteria

The particle may leave the wall by two mechanisms

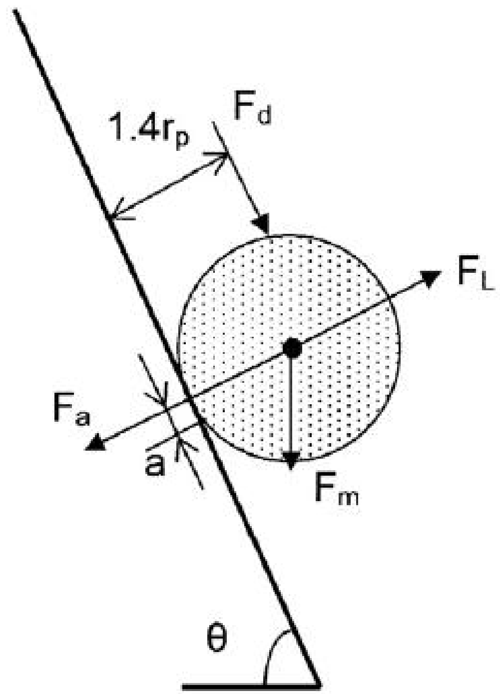
- ***Lift-off*: The *lift* force overcomes the normal component of the *adhesion* and *weight*.**

$$F_v = F_l - F_a - F_m n_z \geq 0, \qquad (1)$$

$n_z = 1$ for a floors, and $n_z = -1$ for a roof ($n_z = \cos\theta$ in general)

- ***Slide-off*: The *lateral force* produced by *drag* and *weight* overcomes the *static friction* force and the particle *slides* on the surface.**

$$|\mathbf{\Pi}_{\|}(\mathbf{F}_d + \mathbf{F}_m)| \geq k_s(-F_v) \qquad (2)$$



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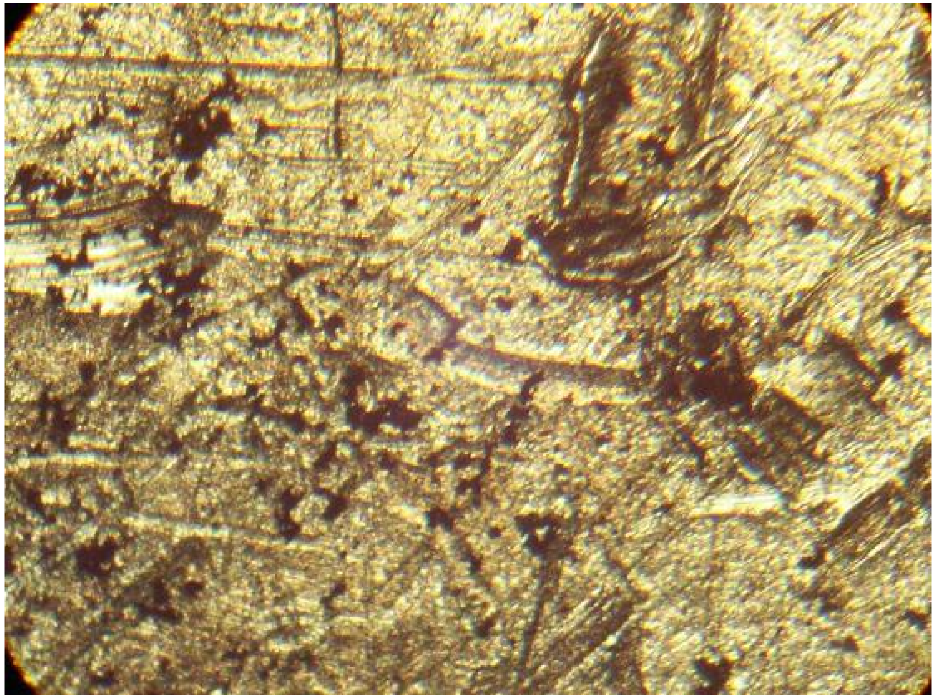
Experimental determination of surface energy

Simple experiments using optical microscopy have shown that particles with $d_p > 30 \mu m$ fall off a steel sheet. From here it can be deduced that $\sigma \approx 3 \times 10^{-6} \mathrm{J/m^2}$.



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Computation of deposition rate

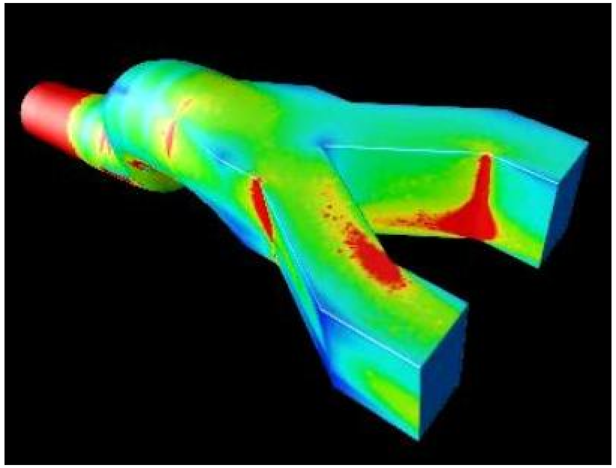
Lift-off and slide-off criteria **are computed and compared to the particle weight.**

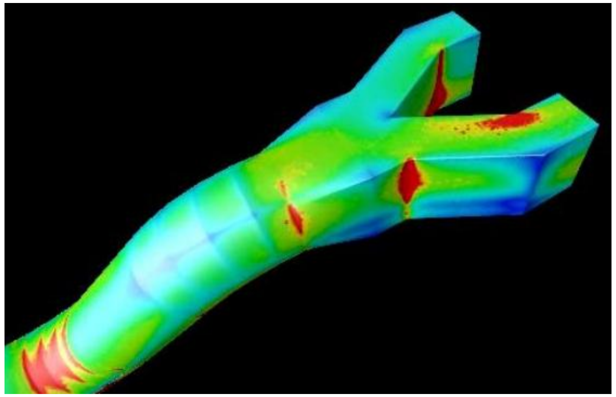
$$F_{\text{lift-off}} = F_v - (F_l - F_a - F_m n_z),$$

$$F_{\text{slide-off}} = |\mathbf{\Pi}_{\|}(\mathbf{F}_d + \mathbf{F}_m)| - k_s(-F_v),$$

$$\textbf{CRIT} = \frac{\max(F_{\text{liftoff}}, F_{\text{slideoff}})}{|F_m|}$$

The colormaps show values of *CRIT* ranging from 0 (blue) to $>$10 o (red). This allows the determination of zones where dust *is likely to accumulate (blue colors)*.





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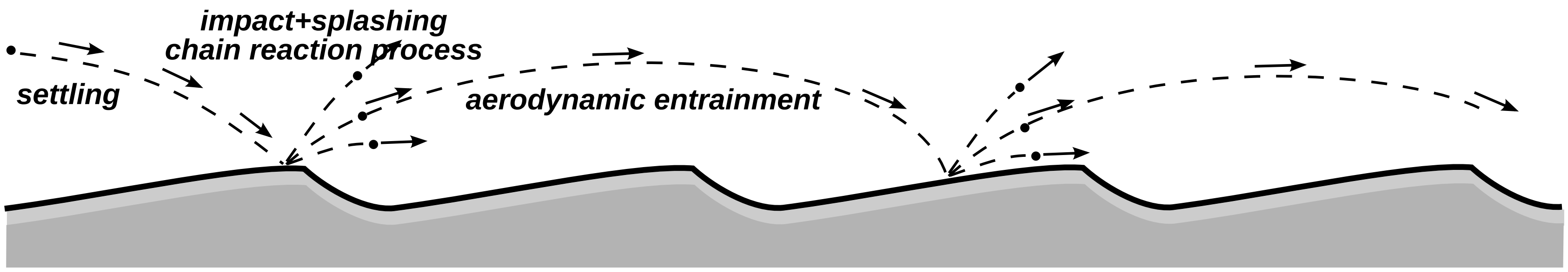
Coarse particulated material. The saltation layer

Most of the material are large particles $d_p > 100\mu m$, typically $d_p \approx 500\mu m$. We focus then on deposition by *gravity*, discarding *adhesion*. In this case the deposition of flow is limited by the physical process of *saltation*. Consider a certain flow $u(z)$ over a plane surface $z = 0$. As particles settle by gravity, they start forming a layer of deposited material. However, this does not means that all the particle settle in the layer. They may be captured in a *saltation layer*. The particles in the layer, are transported by the mechanism of saltation.



The saltation flux

- The total amount of particle material that is transported (steady state, flat surface) is the *saltation flux* and can be expressed as

$$q_s \approx 2\rho_{\rm air} u_*^3 \qquad [\mathrm{kg/sec \cdot m}](\mathrm{Bagnold}, 1936) \tag{3}$$

- u_* is the *friction velocity*.
- For flow in a straight duct under the conditions mentioned above $u_* =$ 0.18 m/s and Q_s = 270 kg/day. *Two orders lower than the particle flow actually transported.*

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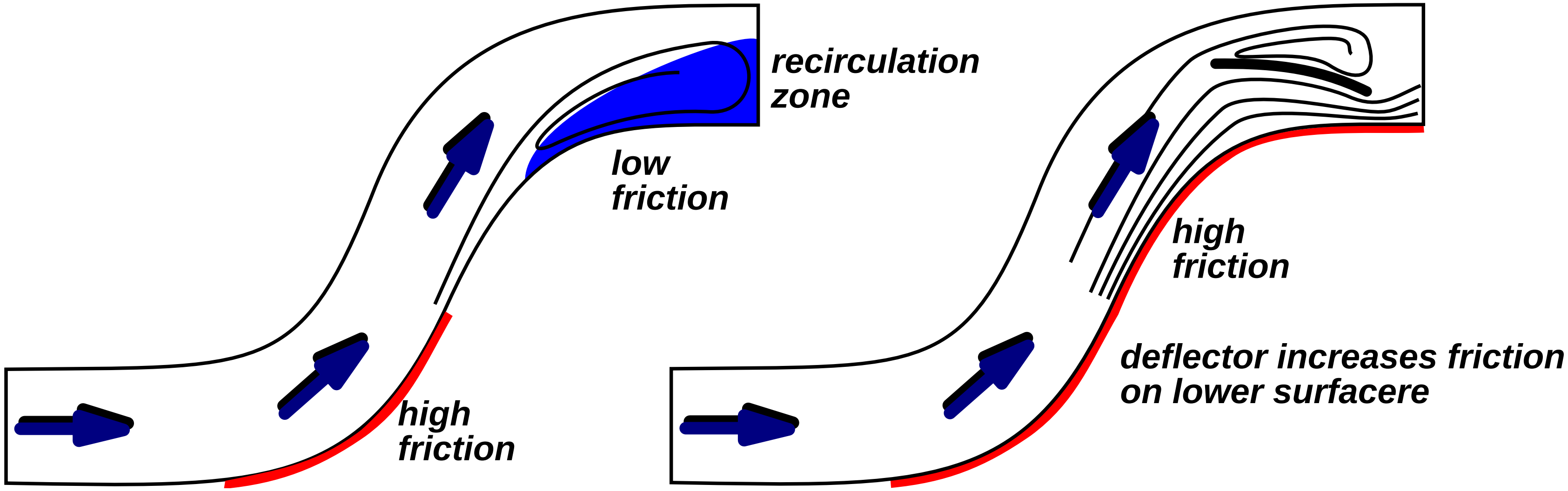
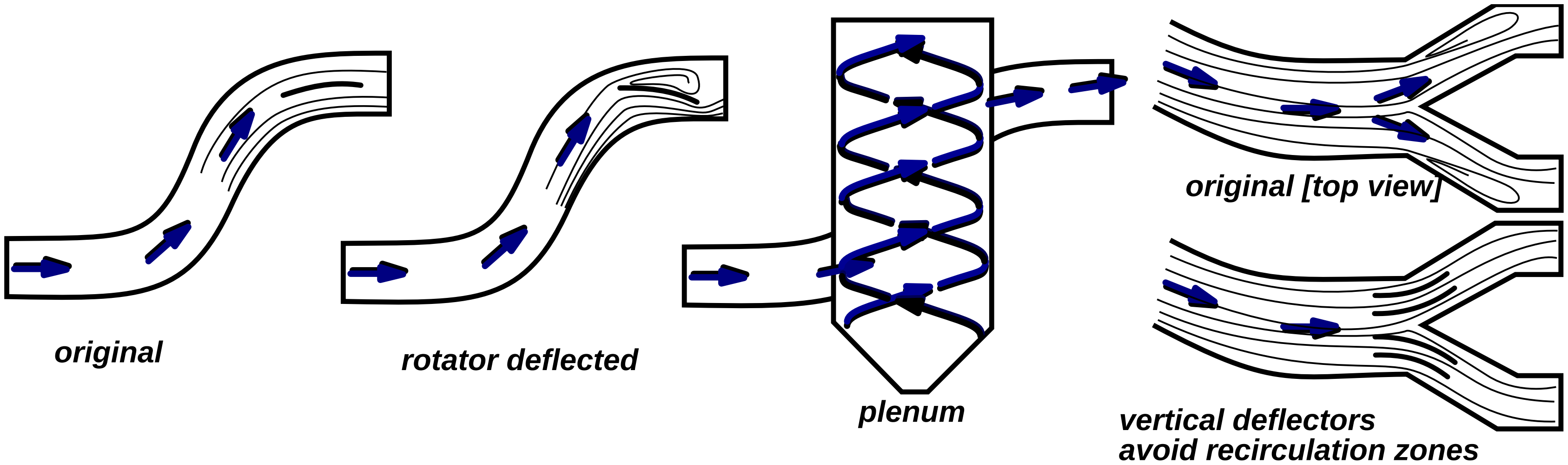
Avoiding deposition

One possibility is the addition of *static deflectors* that increase *wall friction* in compromised parts, like *separated flow zones*.



CFD computations of wall friction and particle trajectories

- **CFD computations can help in predicting *wall friction* at regions where particles may tend to deposit and so to compare differente alternatives.**
- **Several possible geometrical configurations have been proposed: duct+*plenum*, *rotating the upper deflector* (several variants), rotating the upper deflector + *vertical deflectors*.**



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CFD computations of wall friction and particle trajectories (cont.)

- **CFD computations use equal order interpolation *FEM*, *SUPG+PSPG stabilized* with *LES+Smagorinsky turbulence model*.**
- **Particle trajectories are computed with an *element traversal method* with a *Schiller-Naumann model* for the particle drag.**
- **Probability of particle deposition is determined according to *particle flow rate* and *wall shear*.**
- **CFD studies had shown that *rotation of deflectors plus installation of vertical deflectors* is an inexpensive solution that can reduce greatly dust deposition.**

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Schiller-Naumann model

$$
\begin{aligned}
m\dot{\mathbf{v}} &= \mathbf{F}_d + (\rho_\mathrm{p} - \rho_\mathrm{fl})\Omega_\mathrm{p}\mathbf{g},\\
A_p &= \frac{\pi d_p^2}{4},\ \Omega_\mathrm{p} = \frac{\pi}{6} d_p^3,\\
F_d &= {}^1\!/_2 C_d(\mathrm{Re})\, \rho_\mathrm{fl} A_p v_\mathrm{slip} \mathbf{v}_\mathrm{slip},\\
C_d &= \frac{24}{\mathrm{Re}}(1 + 0.15\mathrm{Re}^{0.687}),\\
\mathrm{Re} &= \frac{v_\mathrm{slip}\, d_p}{\nu},\\
\mathbf{v}_\mathrm{slip} &= \mathbf{v} - \mathbf{v}_\mathrm{fl}.
\end{aligned}
$$

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Implicit computation of the drag force

For small particles the drag force is dominant, and the solution of the ODE for the trajectory becomes stiff. The relaxation time, i.e. the time that characteristic time in which the particle reaches the terminal velocity is

$$\tau = v_{\rm slip}/g \propto d_p.$$

If $\tau < \Delta t$ then an implicit scheme is needed for the particle tracking algorithm,

$$m\frac{\mathbf{v}^{n+1} - \mathbf{v}^n}{\Delta t} - \mathbf{F}_d(\mathbf{v}^{n+1}) - m'\mathbf{g} = 0.$$

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Results after inclusion of horizontal and vertical deflectors

This modification (rotation of deflectors plus installation of vertical deflectors) was adopted. After operation of the plant for several month, it was concluded that ***dust deposition was reduced by 1/10th***.

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Results after inclusion of horizontal and vertical deflectors (cont.)

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Results after inclusion of horizontal and vertical deflectors (cont.)

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We made extensive use of *Free Software* (`http://www.gnu.org`) as GNU/Linux OS, MPI, PETSc, GCC/G++ compilers, Octave, Open-DX among many others. In addition, many ideas from these packages have been inspiring to us.