Some remarks on the removal of adhering particles by oscillating air flows

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Particle adhesion – I. van der Waals interaction

F_{vdW} is caused by the interaction of atomic or molecular dipols. According to the ‚macroscopic theory' by Krupp, the force between two planar surfaces is given by

$$F_{vdW} = \frac{h\varpi}{8 \cdot \pi^2 \cdot z_0^3}$$

where $h\varpi$ is the Lifshitz-van der Waals constant (0.6 eV = $9.6 \cdot 10^{-20}$ J) and z_0 the closest distance between the surfaces (0.4 nm).

The more realistic (but still idealized) situation of a sphere of diameter $2 \cdot R$ on a plane is described by

$$F_{vdW} = \frac{h\varpi}{8 \cdot \pi^2 \cdot z_0^2} \cdot R$$

H.C. Hamaker, Physica **4**, 1058 (1937)
H. Krupp, Advances Colloid Interface Sci. **1**, 111(1967)

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Particle adhesion – II. Electrostatic forces

Electrostatic forces are caused by excess charges on the particle surface. The force between a sphere and a plane is given by

$$F_{el} = \frac{q^2}{16 \cdot \pi \cdot \varepsilon_0 \cdot R \cdot \delta} \cdot \frac{\ln\left(1 + \frac{\delta}{z_0}\right)}{\left(\gamma + \frac{1}{2}\ln\left(\frac{2 \cdot R}{z_0}\right)\right) \cdot \left(\gamma + \frac{1}{2}\ln\left(\frac{2 \cdot R}{z_0 + \delta}\right)\right)}$$

with

- q: ‚seen' charge of the particle, typically 20 to 30 % of the total charge Q
- δ: thickness of the charged surface layer ($q(\delta) = q_{surface} \cdot 1/e$)
- ε_0: dielectric constant ($8.86 \cdot 10^{-14}$ As/V cm)
- γ: Euler's constant (0.5772)

H. Krupp, Advances Colloid Interface Sci. **1**, 111(1967)

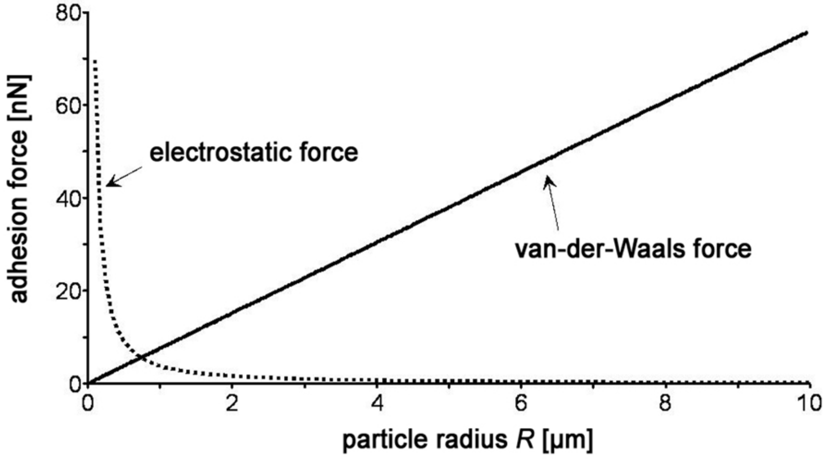
Particle adhesion – II. Electrostatic forces

Quartz particles of 5 to 10 µm diameter were found to have total charges of 500 to 1000 elementary charges.

Experimental studies using polymer particles with sizes ranging from 5 to 30 µm by Kottler et al. showed that the measured F_{el} could be described the stated formula, if the total charge Q was greater than $10^4\ q_0$ (q_0 = elementary charge).

F_{el} was equivalent to F_{vdw}, if the total charge Q was smaller than $10^4\ q_0$.

In the case of R > 5 µm, F_{el} was 100 times smaller than F_{vdw}.



W. R. Harper, Advances in Physics **6**, 365 (1957)
L. B. Loeb, *Static Electrification*, Springer, 1959
W. Kottler, H. Krupp und H. Rabenhorst, Z. angew. Physik **24**, 219 (1968)
H. Rumpf, *Particle Adhesion,* Proc. *Agglomeration 77*, 2nd Symp. on Agglomeration, Atlanta 1977

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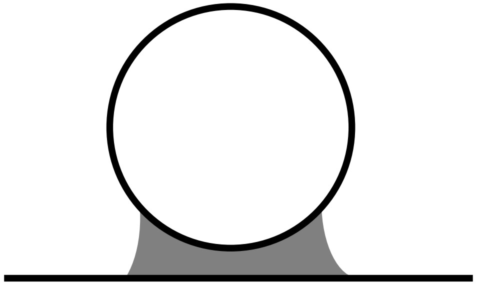
Particle adhesion – III. Capillary forces

Capillary forces are caused by liquid between particle and surface. Assuming idealized geometry – spherical particle and plane – the capillary force is given by between a sphere and a plane is given by

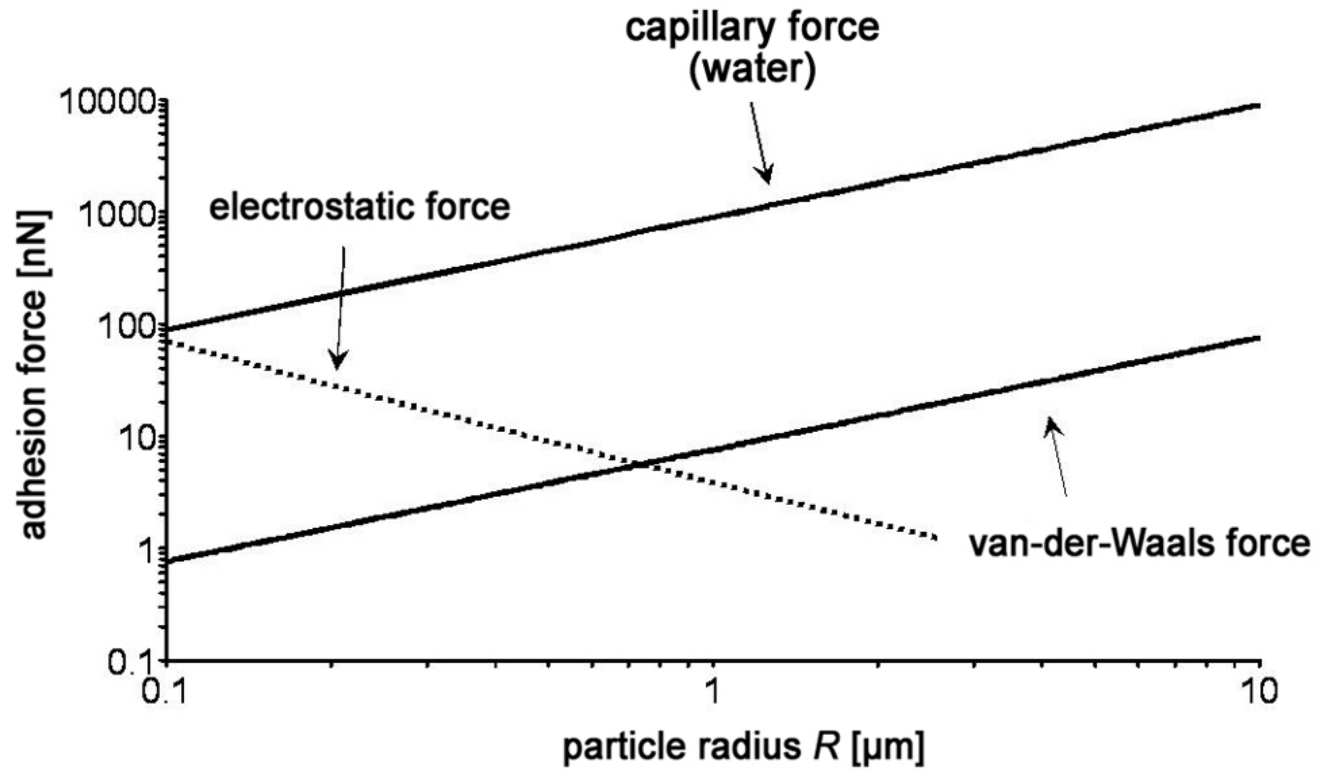


$$F_{cap} = 4\pi \cdot \gamma \cdot R$$

with γ: Surface tension
R: Particle radius

F. D. Bowden und T. Tabor, R*eibung und Schmierung fester Körper,* Springer, 1959
H. Rumpf, *Particle Adhesion,* Proc. *Agglomeration 77*, 2nd Symp. on Agglomeration, Atlanta 1977

Particle adhesion – Dependence on particle size



Particle removal by an air flow

Particle removal by an air flow is due to **drag** and **buoyant forces**. Both forces are derived from the Bernoulli equation

$$p(x,y,z)+\frac{1}{2}\cdot\rho_a\cdot u(x,y,z)^2 = p_0 = const$$

with

	ρ_a:	density of air
	$u(x,y,z)$:	velocity of the air flow at point (x,y,z)
	p_0:	ambient pressure (u = 0)

The dynamic pressure of the air flow is then given by $p_d = \frac{1}{2}\cdot\rho_a\cdot u^2 = p_0 - p$

while the static pressure of the air flow is given by $p_s = p = p_0 - p_d$

W. Bohl, *Technische Strömungslehre,* Vogel, Würzburg 1987

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Particle removal by an air flow – I. Drag forces

The total drag force is calculated by integrating the dynamic pressure over the ‘in stream’ area of the particle (frontal area):

$$F_d = \oiint_A \frac{\rho_a}{2} \cdot u(z,y)^2 \cdot dz \cdot dy$$

Problem: *u(z,y)* cannot be determined for real particles which may have complex shapes and rough surfaces. For arbitrarily shaped bodies, the influence of these parameters is integrally described by the drag coefficient c_w, and the drag force F_d is described by the expression

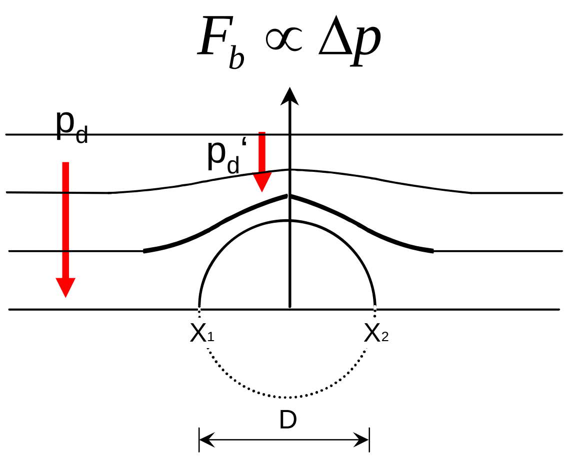
$$F_d = c_w \cdot \frac{\rho_a}{2} \cdot {u_\infty}^2 \cdot A$$

with u_∞ the velocity of the undisturbed air flow, and A the frontal area of the particle.

Particle removal by an air flow – I. Buoyancy

Buoyancy effects are also derived from the Bernoulli equation. A practical expression is

$$F_b = c_b \cdot \frac{\rho_a}{2} \cdot u_\infty{}^2 \cdot A$$



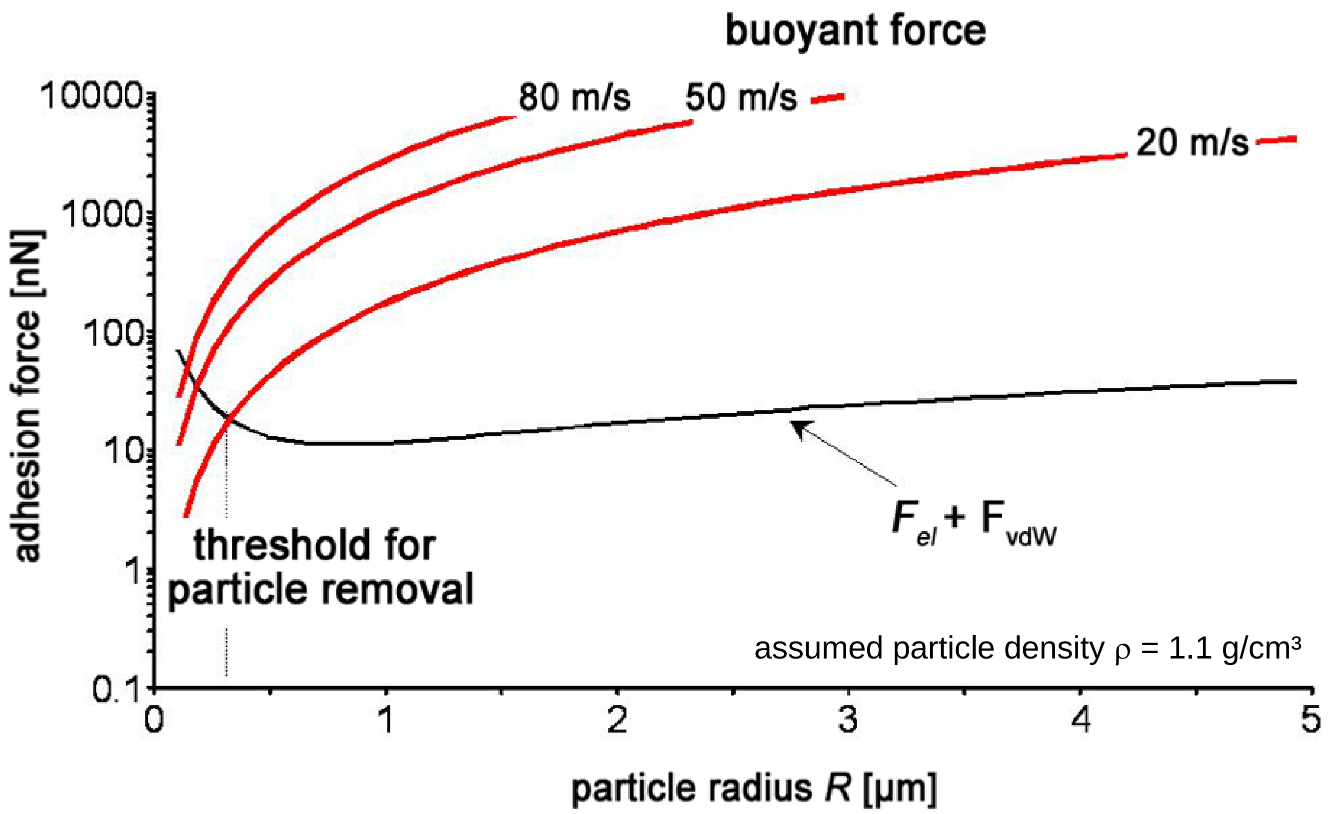
with u_∞ the velocity of the undisturbed air flow, and A the frontal area of the particle.

In this expression, c_b is the buoyancy coefficient.

For spherical particles on a plane, c_b can be assumed to $c_b \approx 0.25$.

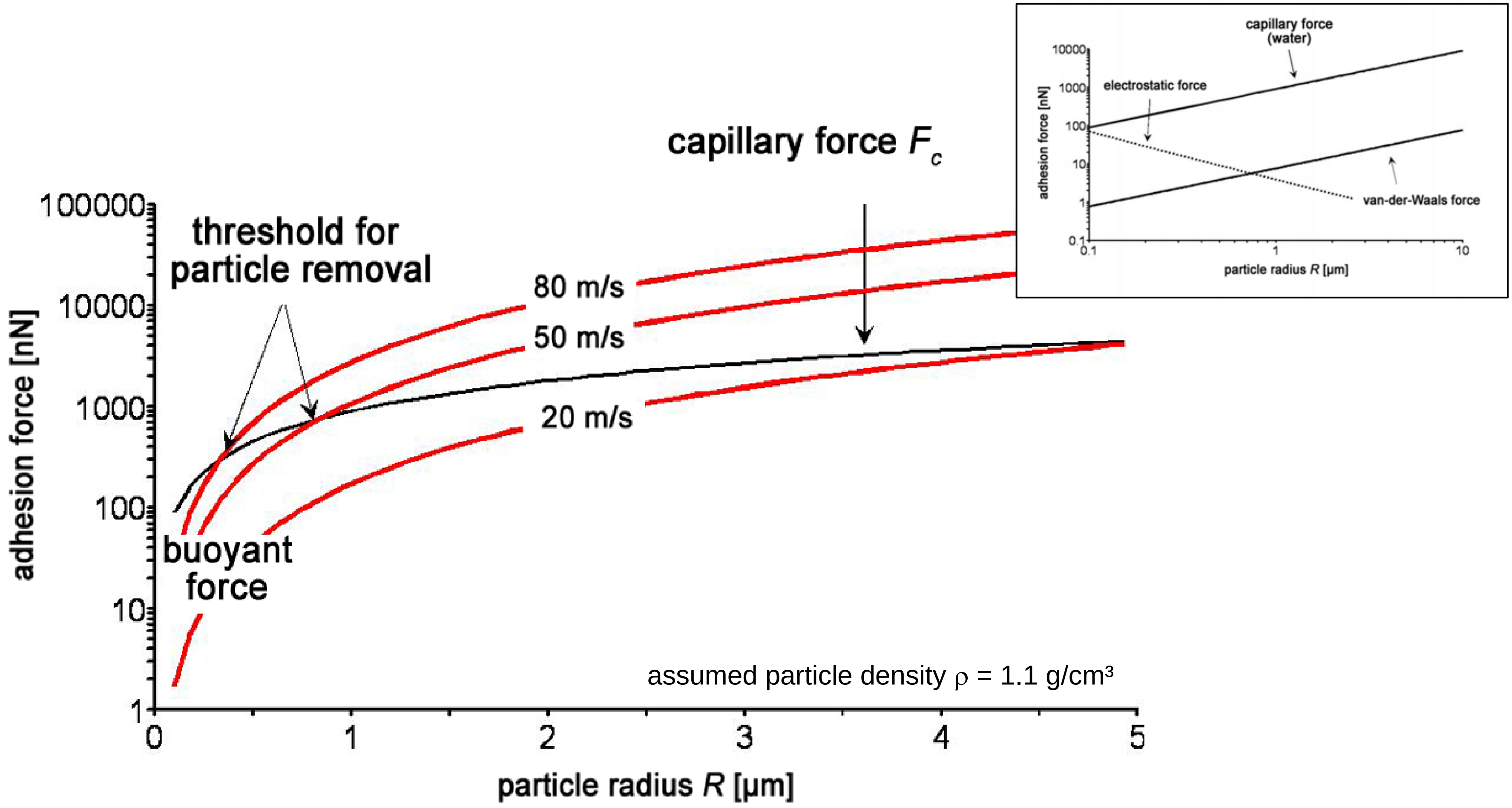
W. Bohl, *Technische Strömungslehre,* Vogel, Würzburg 1987

Particle removal by an air flow – Case 1: Only F_{el} and F_{vdw}



⇒ Air flows of rather low velocities can be expected remove even submicron particles efficiently

Particle removal by an air flow – Case 2: (Additional) capillary forces

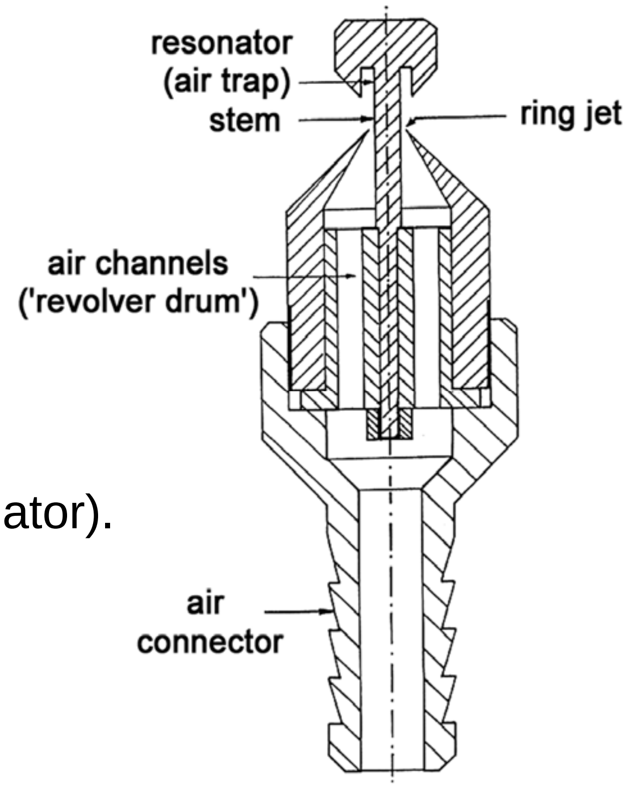


⇒ High speed air flows are required, if capillary forces act.

Oscillating high-speed air flows and ultrasound

Oscillating air flow removal systems are occasionally found in (textile) industry for the cleaning of, e.g., delicate technical fabrics.
But frequencies and air velocities are low.

As a potential source for **high-speed oscillatting air flows**, a hydrodynamic device designed as a ‘pneumatic flip-flop’ was considered.



Working cycle:

1. Pressurized air is guided into a flow trap (resonator).
2. Pressure in the flow trap increases and
3. the air flow is diverted out of the air gap.
4. Pressure in the flow decreases and
5. cycle resumes.

Y. Borisov,
in: *Sources of high intensity ultrasound, Vol. 1*, Rozenberg (ed.), Plenum Press, New York 1969

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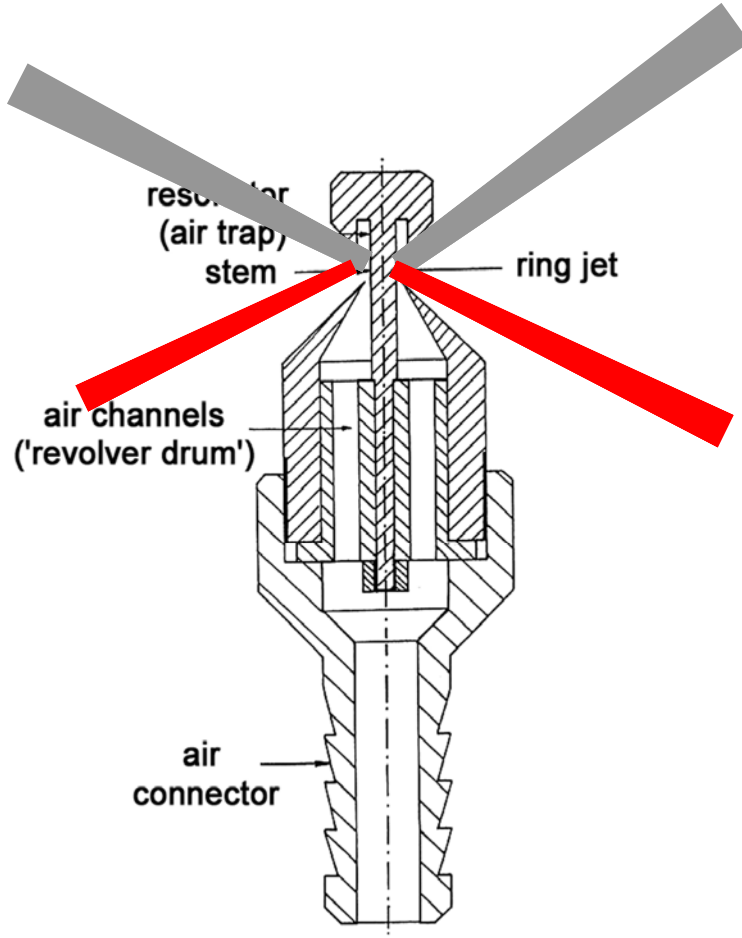
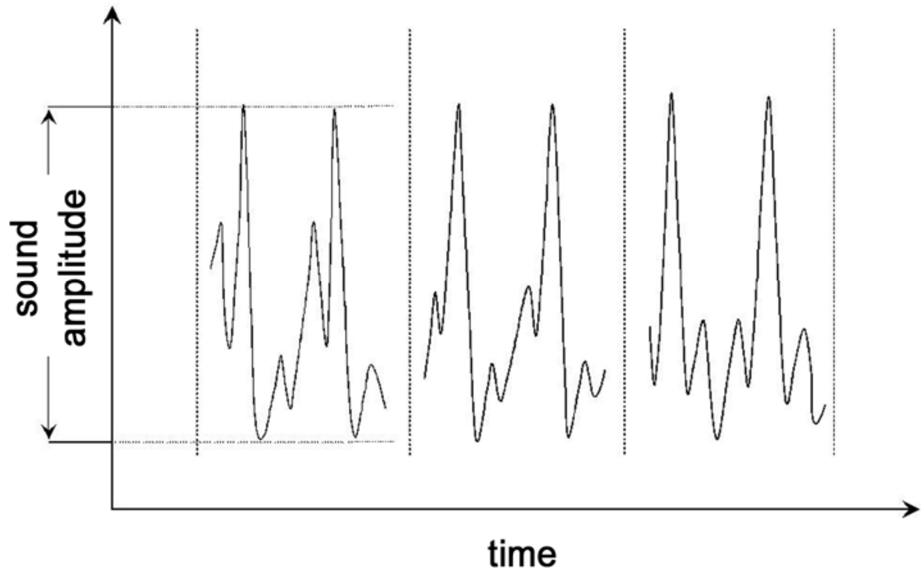
Oscillating high-speed air flows and ultrasound

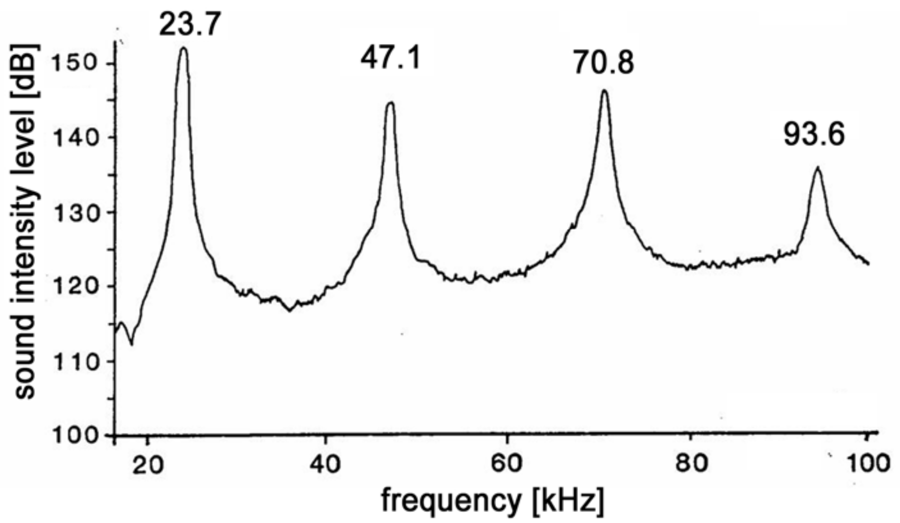
Due to the collapse of the forward facing air flow, an ultrasonic wave in backward direction is generated!

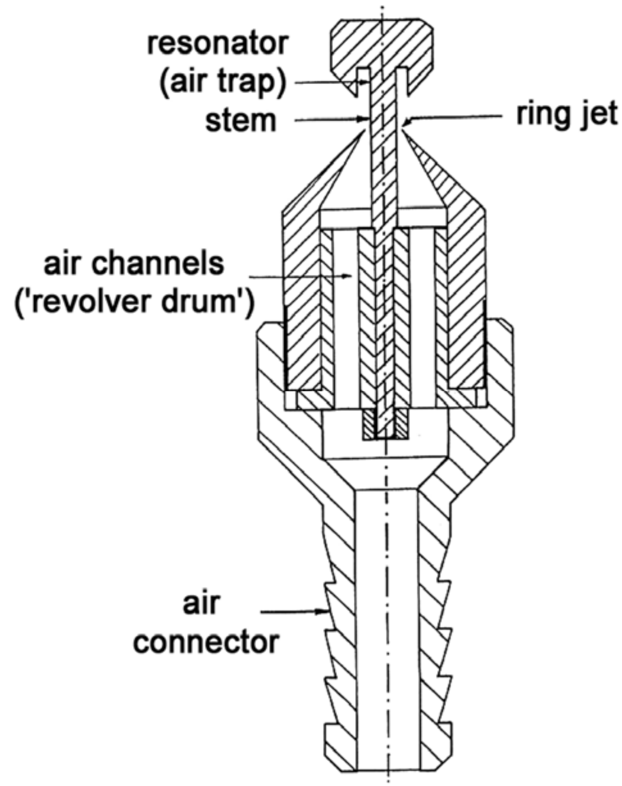
Can we use the ultrasonic wave/field for particle removal similar to ultrasonic cleaning in ‚baths‘



Characteristics of the generated ultrasound wave







Forces effected by ultrasonic waves

If one assumes a harmonic signal, the force on a particle is given by

$$F_{US} = m \cdot a = m \cdot \omega \cdot v = m \cdot (2\pi \cdot f) \cdot v$$

where *m* is the mass of the particle, *f* the frequency of the ultrasonic wave and *v* the sound velocity. The sound velocity is derived from

(a) the sound intensity level $$L = 20 \cdot \log\left(\frac{p}{p_0}\right)$$

and (b) the acoustic impedance $$Z_0 = \frac{p}{V} = \rho_a \cdot c$$

p: pressure of the sound wave

p_0: hearing threshold at 1 kHz; $p_0 = 2 \cdot 10^{-5}$ N/m²

ρ_a, c: density of air and speed of sound in air $\Rightarrow Z_0 = 408$ N·s/m³

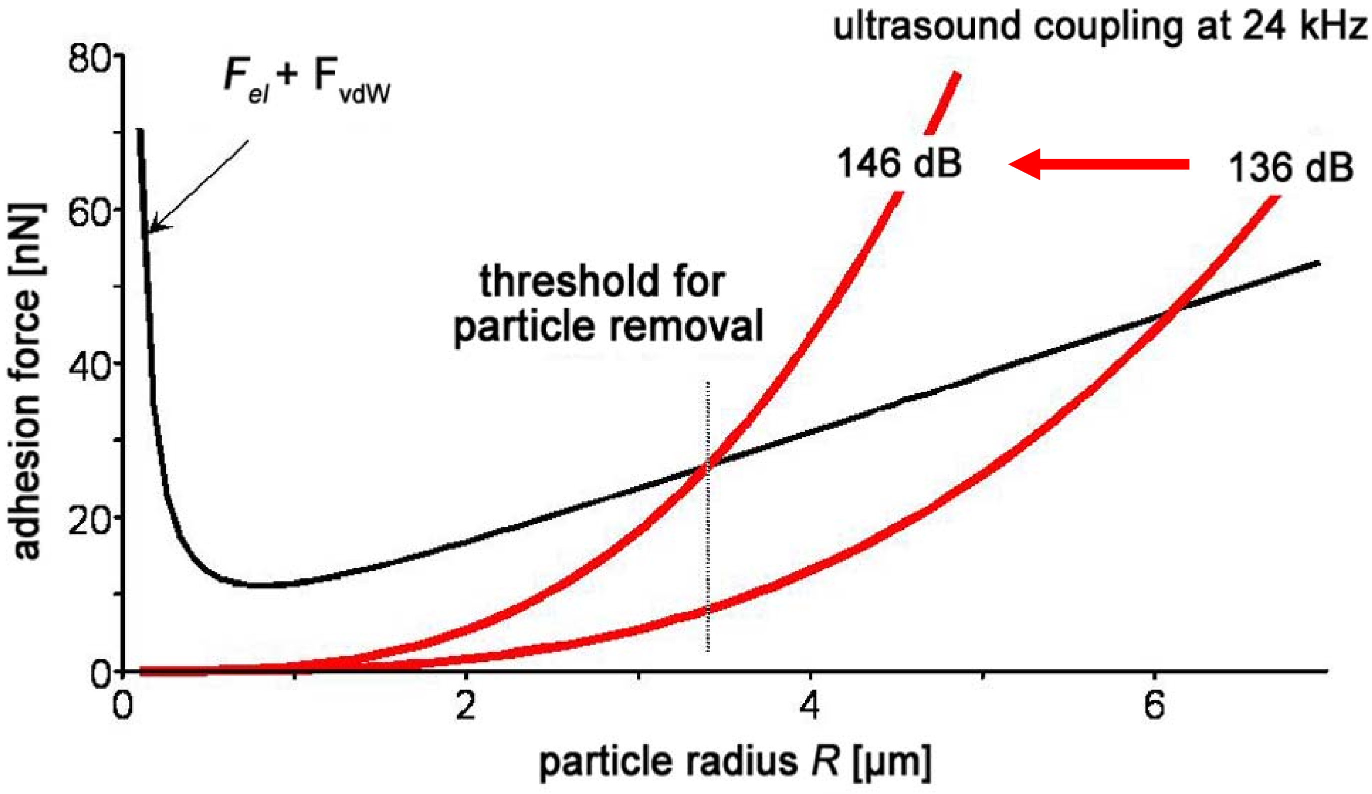
Forces effected by ultrasonic waves

With the given values of ρ, c, p_0 and experimentally determined values of the sound pressure p at the harmonics, one obtains:

- sound velocity v = 0.296 m/s
- effective acceleration at 24 kHz (136 dB) $a \approx$ 45,000 m/s²
- effective acceleration at 94 kHz $a \approx$ 175,000 m/s²

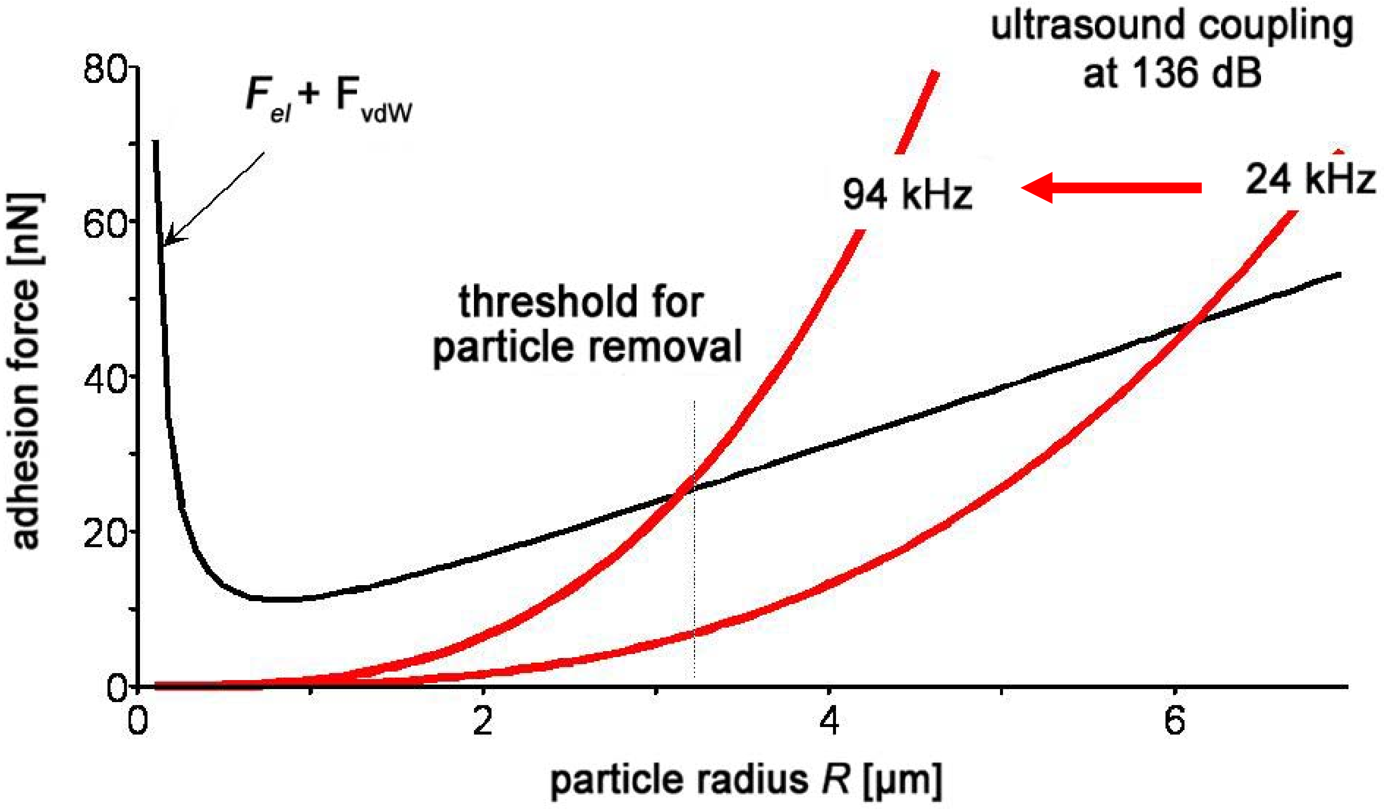
Assuming spherical particles and a particle density of 1.1 g/cm³, the resulting force F_{US} can be estimated and again compared to determining adhesion forces.

Particle removal by ultrasound – Case 1: Only F_{el} and F_{vdw}



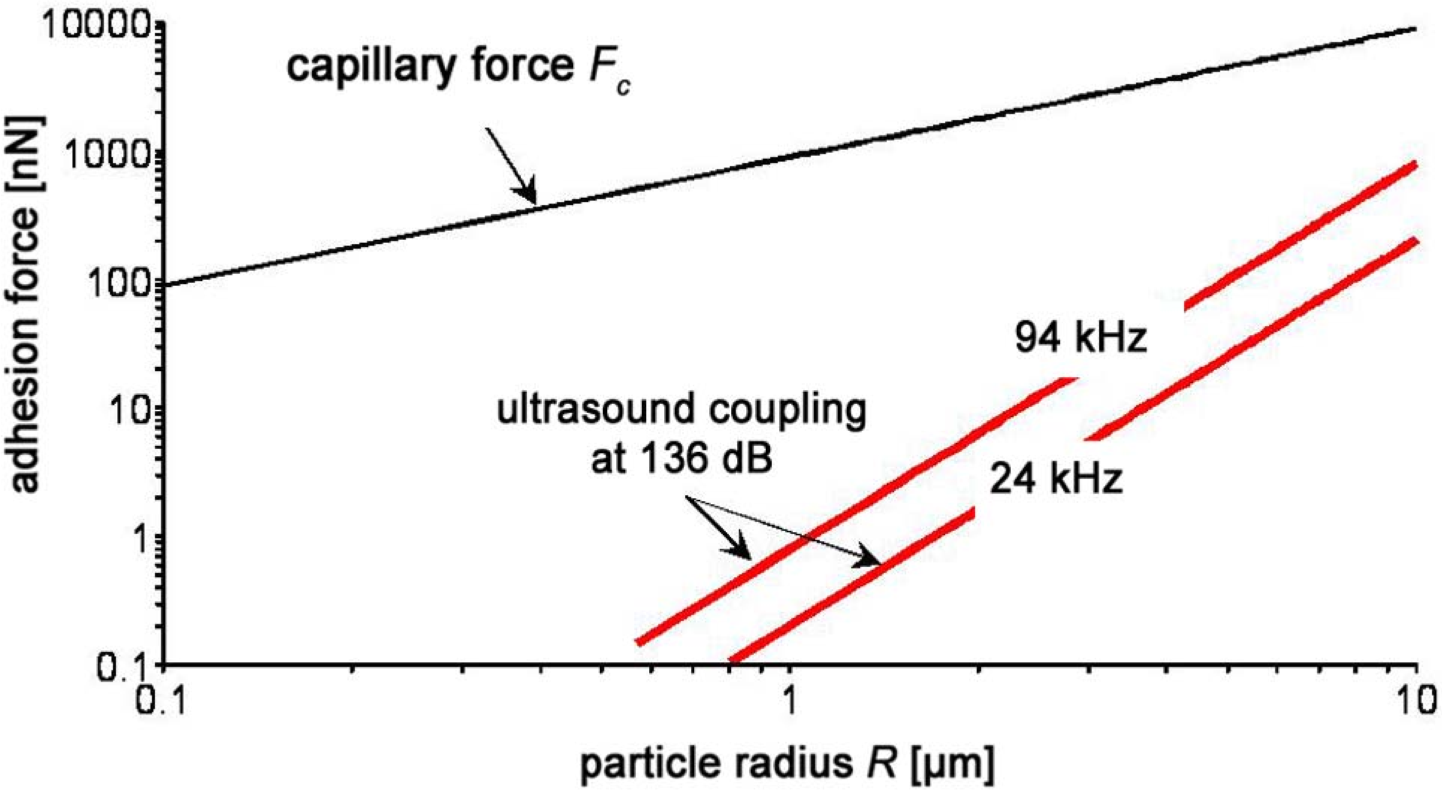
Increase of sound pressure moves the threshold for particle removal to smaller particles, but the threshold is still way above 1 µm

Particle removal by ultrasound – Case 1: Only F_{el} and F_{vdw}



The threshold for particle removal can be shifted to smaller particles also by using high US frequencies.

Particle removal by ultrasound – Case 2: (Additional) capillary forces



Ultrasound alone does not suffice to overcome capillary adhesion forces of particles in the micron and submicron size range

Thank you for your attention!

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