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Adhesion of Particles from Wood Combustion on Precipitation Surfaces

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1 Introduction

Particle properties play an important role in particle removal systems. An ideal operation of electrostatic precipitators (ESP) can only be achieved in a certain bandwidth of the electric conductivity of the particles [1]. Additionally, adhesion of particles is a key property in dust precipitation. It determines the minimum pressure impulse or the mechanical force needed to remove dust layers from fabric filters and ESP. Weak adhesion can cause re-entrainment in ESP, while high adhesion on the precipitation surface may lead to damages in ESP and fabric filters, potentially leading to the destruction of filter bags through conglutination.
For the operation of precipitators for wood combustion, it is essential to distinguish different combustion regimes [2] with dedicated particle categories [3] as follows:

1. Inorganic particles (salts) from almost-complete combustion
2. Soot from combustion with local lack of oxygen at high combustion temperatures
3. Condensable organic compounds (COC) formed at low combustion temperature.

It was shown in [3] that the electric conductivity of the particle categories varies by several orders of magnitude. The aim of the present work is to investigate and characterise the adhesion of particle layers from wood combustion. The adhesion of particles, especially in layers, is complex. Therefore, theoretical models to describe and calculate particle adhesion are scarce and it is hardly possible to reliably calculate adhesion of particle layers [4]. There are certain models for specific cases e.g. [5–7]. However, the number of factors is too high to adapt them in practice and hence experiments to characterise the properties are necessary and were conducted in the present work.

2 Method

Dust layers of one to two millimeters were collected in a laboratory scale tube ESP on bare steel and on electro polished steel. The dust samples were investigated during exposition to pressure impulses in a test channel of 100 mm x 16 mm x 18 mm in parallel to the dust layer. With this setup, the cleaning efficiency of the pressure impulse can be determined optically and quantified by the percentage of the cleared area as a function of the applied pressure impulse. According to the experimental results referred to in [1], the cleaning force needs to be increased by a factor of 10 to increase the cleaning efficiency from 50% to 98%. Consequently, it is possible to distinguish between different particle categories even in the case of relevant fluctuations and uncertainties.
Additional experiments with ultrasonic vibrations were made to determine adhesion according to acceleration forces. These experiments were carried out with an advanced ultrasonic dry-cleaning device, which finds the resonance of the test surface independently. Using this device, we measured about 1000 times the acceleration of gravity on our experimental surface.

3 Results

The results show that the pressure impulse needed to achieve a certain cleaning efficiency for the different particle layers varies by three orders of magnitude with increasing pressure impulse needed from soot to salt and to COC (Fig. 1).

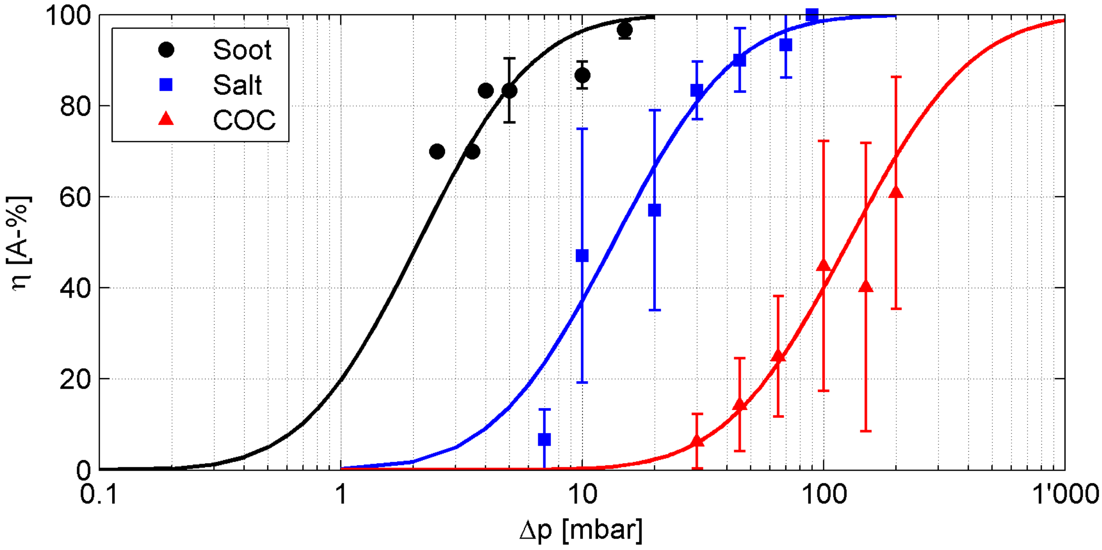


Fig 1: Cleared area as a function of the applied pressure impulse, depending on the particle type on bare steel.

While the salt layer exhibits a medium adhesion, which can be characterised by a pressure for 50% cleaning efficiency according to area of app. 20 mbar, the required pressure impulse of app. 2 mbar is at the lower range of the experimental setup for soot. Consequently, soot is also expected to be potentially removed by re-entrainment in the ESP, which is not the case for layers of salts or COC. COC layers reveal high fluctuations at the upper boundary of the setup with an average of app. 200 mbar needed for 50% cleaning efficiency (Fig. 1).

By comparing the results of the cleaning of the three layers by ultrasonic vibration as shown in Table 1, salt shows the highest efficiency by acceleration which can be explained by its low porosity. Adhesion in salt layers is dominated by van der Waals forces. The porosity of soot is high as shown in Table 1. This causes a low density and an elastic behaviour. Consequently low detachment efficiencies due to acceleration forces are found for soot.
Liquid compounds increase the adhesion of COC. This leads to low efficiency in the ultrasonic vibration experiment for COC layers.

Table 1: Detachment due to acceleration by ultrasonic vibrations depending on the particle type on electro polished steel. [a-%] = % of area, [m-%] = mass-%.

<table>
<tr><th></th><th>Soot</th><th>Salt</th><th>COC</th></tr>
<tr><td>Detachment efficiency η at a ≈ 1000·g</td><td>25 [a-%]</td><td>55 [m-%]</td><td>22 [m-%]</td></tr>
<tr><td>Density ρ_{Layer} [g/cm^3]</td><td>0.1</td><td>1.48</td><td>1.0</td></tr>
<tr><td>Porosity ε</td><td>94%</td><td>25%</td><td>17%</td></tr>
<tr><td>Physical properties</td><td>high elasticity & low density</td><td colspan="2">low elasticity & high density</td></tr>
</table>

4 Conclusions

The presented investigation allow the following conclusions on adhesion:

1. Forces needed for dedusting precipitator surfaces depend on adhesion.

2. Adhesion varies by more than three orders of magnitude depending on
   – the particle type and
   – the porosity of the particle layer.

3. For soot, the layer build-up in ESP is determined by its high electrical conductivity forming a layer with high porosity and weak adhesion.

4. Salt and Condensable Organic Compounds (COC) build a homogenous layer.
   – For salts, van der Waals forces determine the adhesion.
   – For COC, liquid compounds significantly increase adhesion.

5. Only minor influences on adhesion are found by
   – Surface roughness and
   – Flue gas humidity (determined by the water content of the fuel).

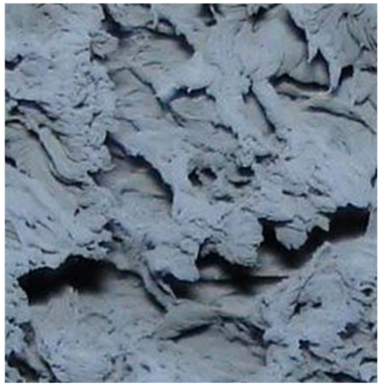
To use the presented results to dedust electrostatic precipitators or fabric filters, the following points have to be considered:

- The cleaning effect of aerodynamic drag depends on area (d^2).
- The cleaning effect of acceleration depends on mass (d^3) and porosity.

- Aerodynamic drag efficiency decreases from soot with high porosity to salt and to COC.
- Acceleration force is suited for salt removal, but limited for soot due to a high porosity and COC due to high adhesion.

5 References

[1] White, H. J. (1963). Industrial Electrostatic Precipitation. Oxford.
[2] Nussbaumer, T. (2003). Combustion and Co-combustion of Biomass: Fundamentals, Technologies, and Primary Measures for Emission Reduction. Energy & Fuels 17: 1510-1521.
[3] Lauber, A. & T. Nussbaumer (2009). Design and operation characteristics for electrostatic precipitators for wood combustion particles as function of combustion conditions. 13th ETH Conference on Combustion Generated Particles, Zürich.
[4] Hinds, W. C. (1999). Aerosol Technology. New York.
[5] Gradon, L. (2009). Resuspension of particles from surfaces: Technological, environmental and pharmaceutical aspects. Advanced Powder Technology 20(1): 17-28.
[6] Blanchard, D., et al. (2002). Correlation Between Current Density and Layer Structure for Fine Particle Deposition in a Laboratory Electrostatic Precipitator. IEEE Transactions on Industry Applications 38(3): 832-839.
[7] Friess, H. & G. Yadigaroglu (2002). Modelling of the resuspension of particle clusters from multilayer aerosol deposits with variable porosity. Aerosol Science 33: 883-906.



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SWITZERLAND

15th ETH Conference on Combustion Generated Nanoparticles
Zurich, 26 – 29 June 2011

Lucerne University of Applied Sciences and Arts

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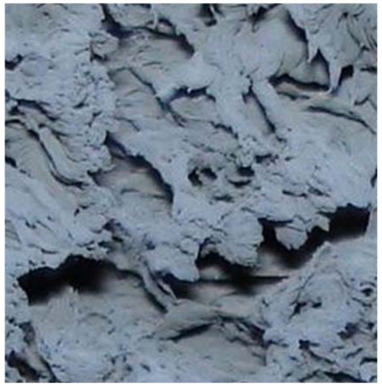

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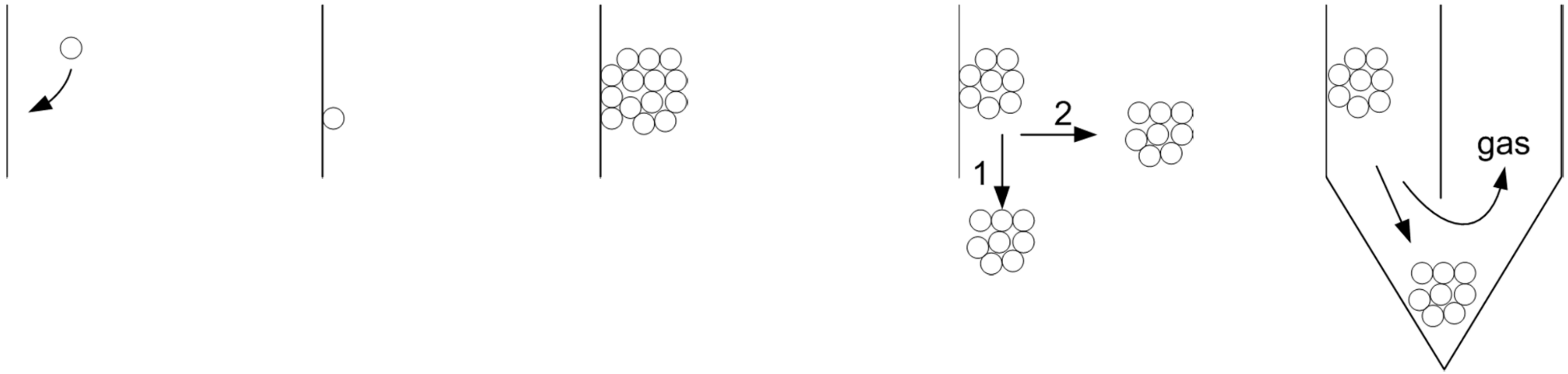
Process Steps in Particle Separation

Precipitation				Dedusting*	
Transport →	Deposition →	Agglomeration	→	Detachment →	Removal
Adhesion				1. Aerodynamic drag (Pressure impulse) 1. Accelaration (Ultrasonic Vibr.)	Inertia



→ Forces needed for dedusting precipitator surfaces depend on adhesion.

*In case of particles including non-combustible ones, for soot only, the particle layer can be combusted

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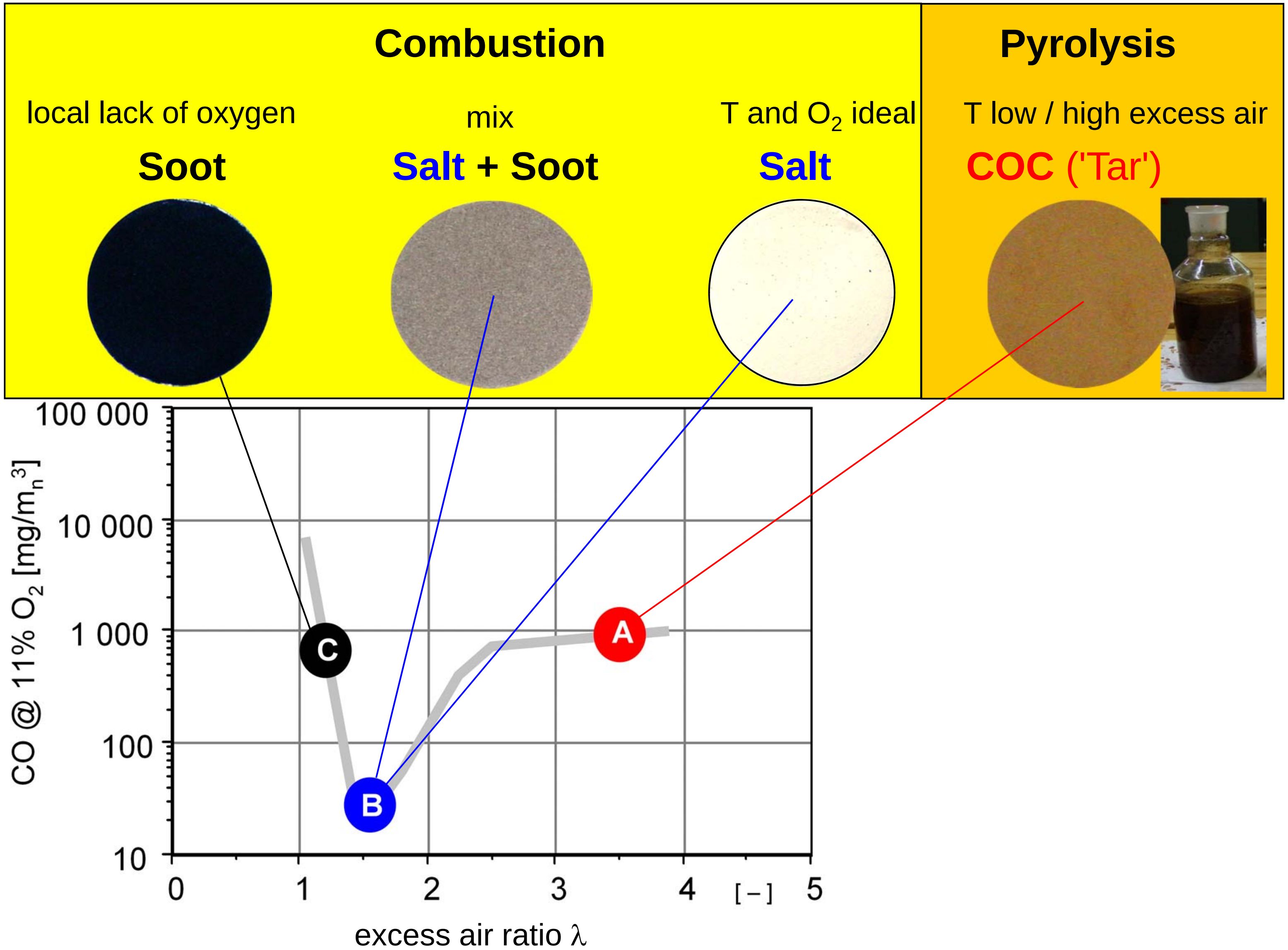
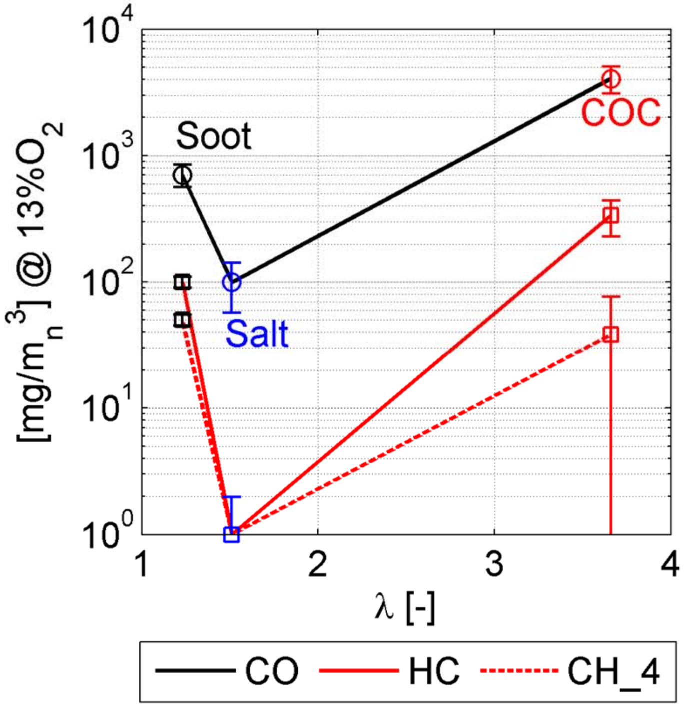
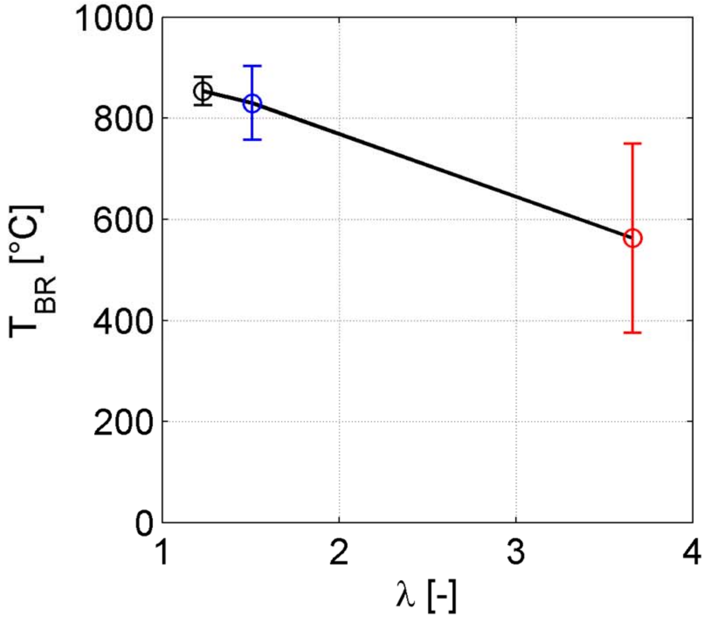
Particle Types



[Nussbaumer & Lauber, 2010]
[Nussbaumer, *2003*]

Gas and Chemical Analysis

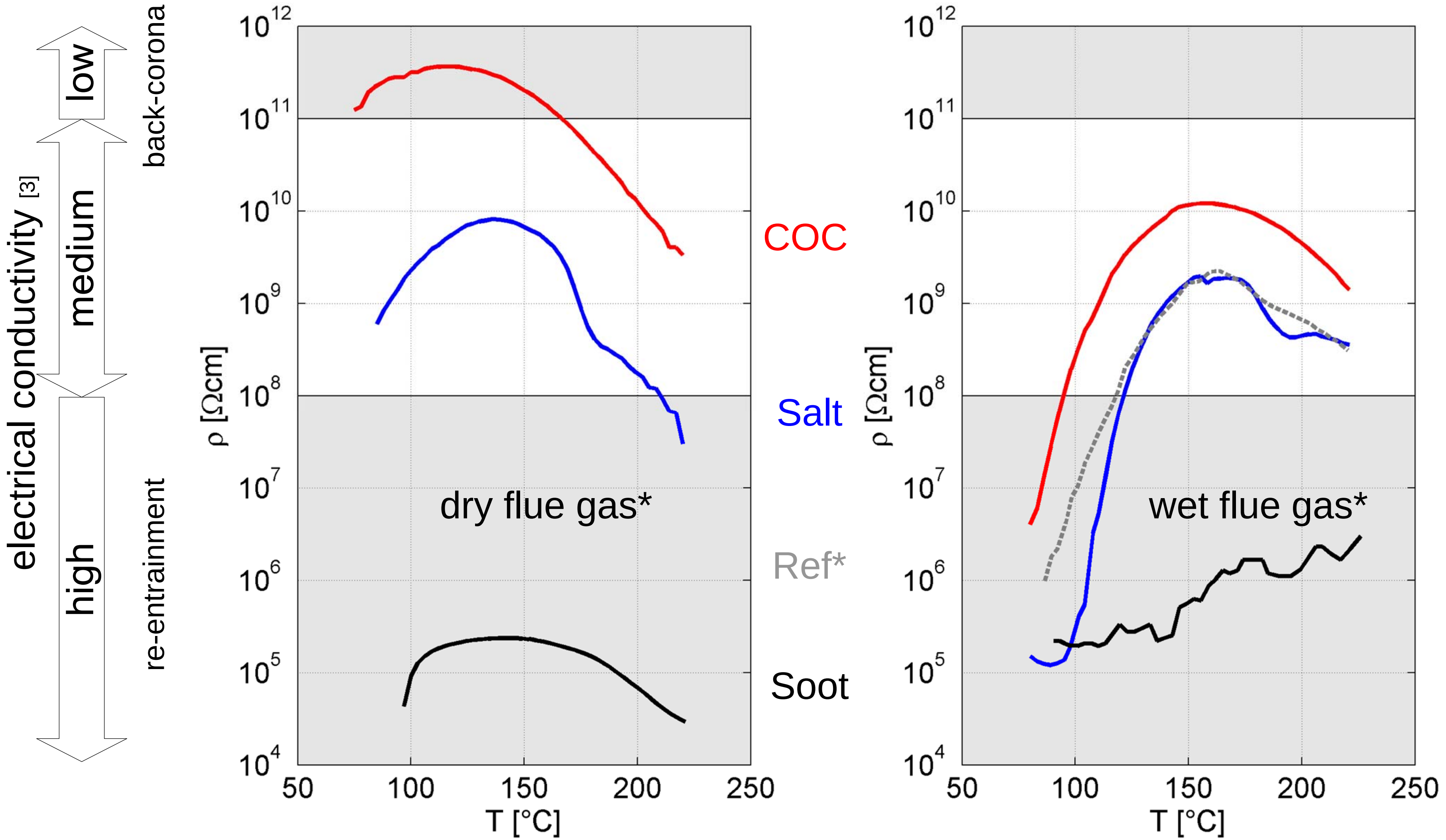




		Soot	Salt	COC
TOC	[m-%]	49	13	45
C/H	[mol/mol]	6.5	-	1.3
d_g	[nm]	200	65	80
c_m	[mg/m³] @ 13% O_2	70	20	30

[Lauber & Nussbaumer, 2009]

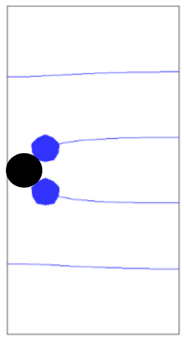
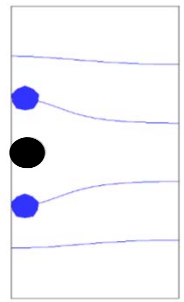
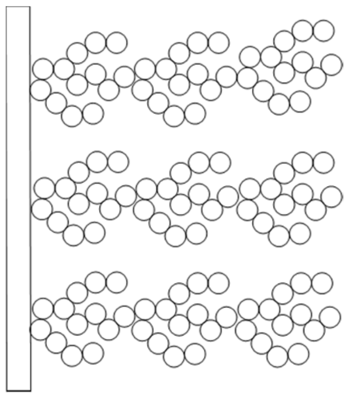
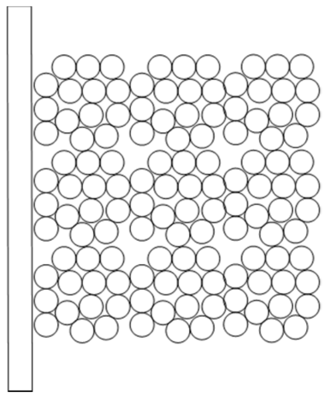
Particle Property: Specific Dust Resistivity



*Dry: 5 vol.-% H_2O e.g. excess air ratio 3 & wood moisture content 5%
*Wet: 20 vol.-% H_2O e.g. excess air ratio 1.2 & wood moisture content 50%
*Ref: 13 vol.-% H_2O: excess air ratio 1.5 & wood moisture content around 30%

[Lauber & Nussbaumer, 2009]
[3]: Parker, 1997

Layer Structures in ESP

	Conductive particles: →‘dendritic‘ build-up	Normal or isolating particles: → homogeneous build-up
Particle influence on electric field:		
Resulting layer structure:		
Particle Category:	Soot	Salt & COC

acc.: [Blanchard et. al., 2002]
[Lauber & Nussbaumer, 2009]

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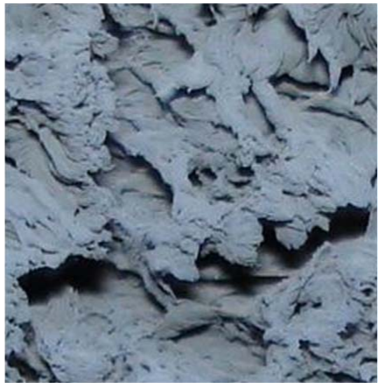

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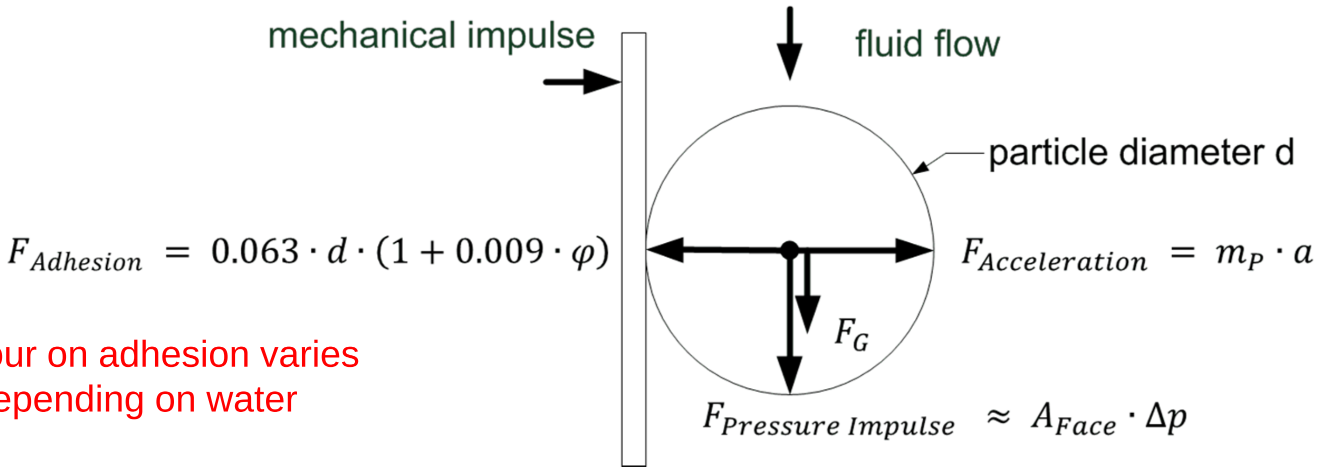
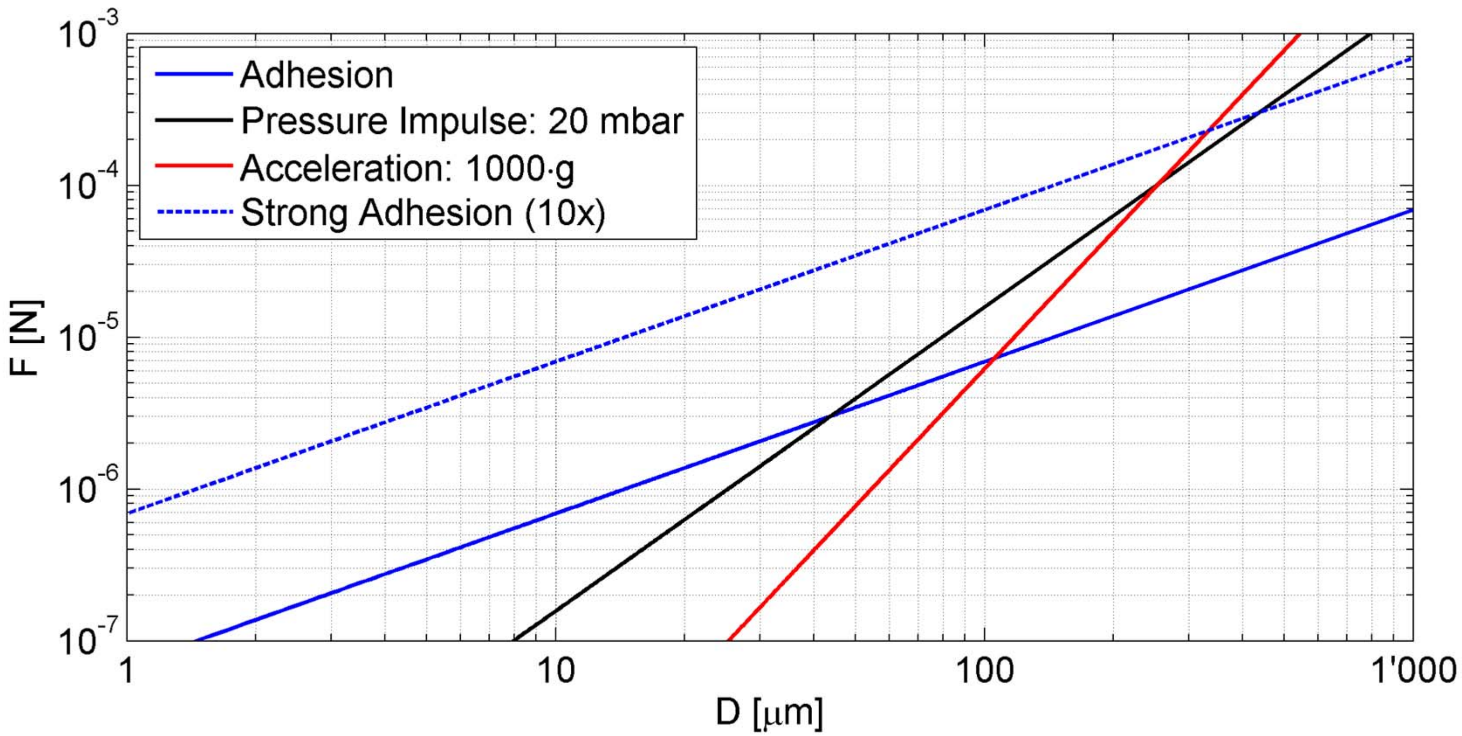
Forces on Particle

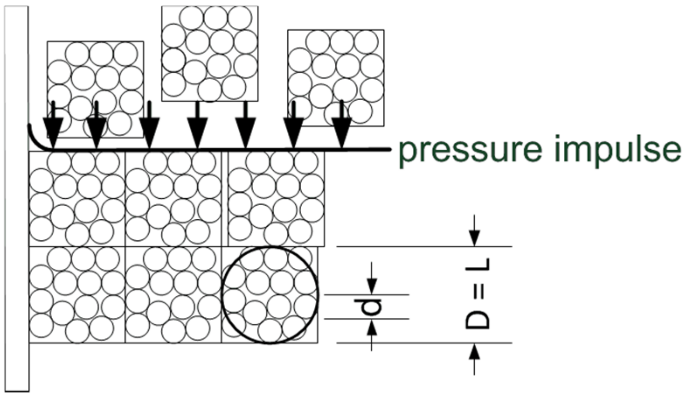
Effect		Force	prop. to:
Adhesion (Precipitation)		- van der Waals - electrostatic - capillarity	**d**
Detachment (Dedusting)	aerodynamic drag	- air current - pressure impulse	**d²**
	acceleration	- gravity - mechanical impulse - vibration - centrifugal force	**d³**



→ influence of water vapour on adhesion varies between 4 and 20 % depending on water content of wood

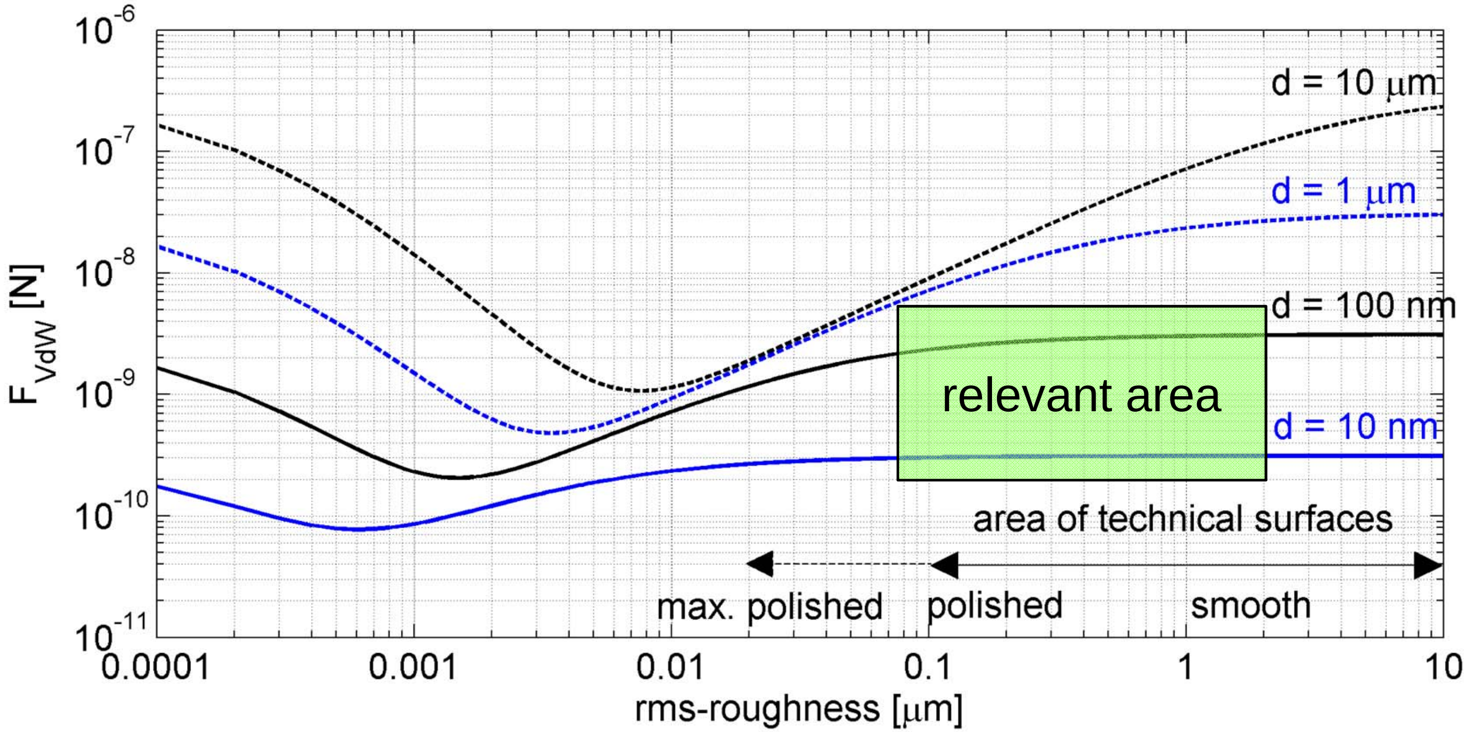
Adhesion vs. Detachment



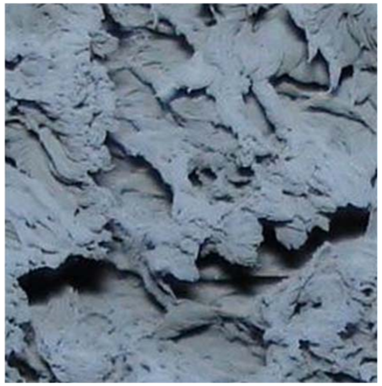


Influence of Surface Roughness (e.g. in ESP)

(Rabinovich equation)



→ minor adhesion reduction due to polishing expected



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Experimental Setup: 1. Particle Sampling

ESP:

L 1000 [mm]

D 100 [mm]

u 1 [m/s]

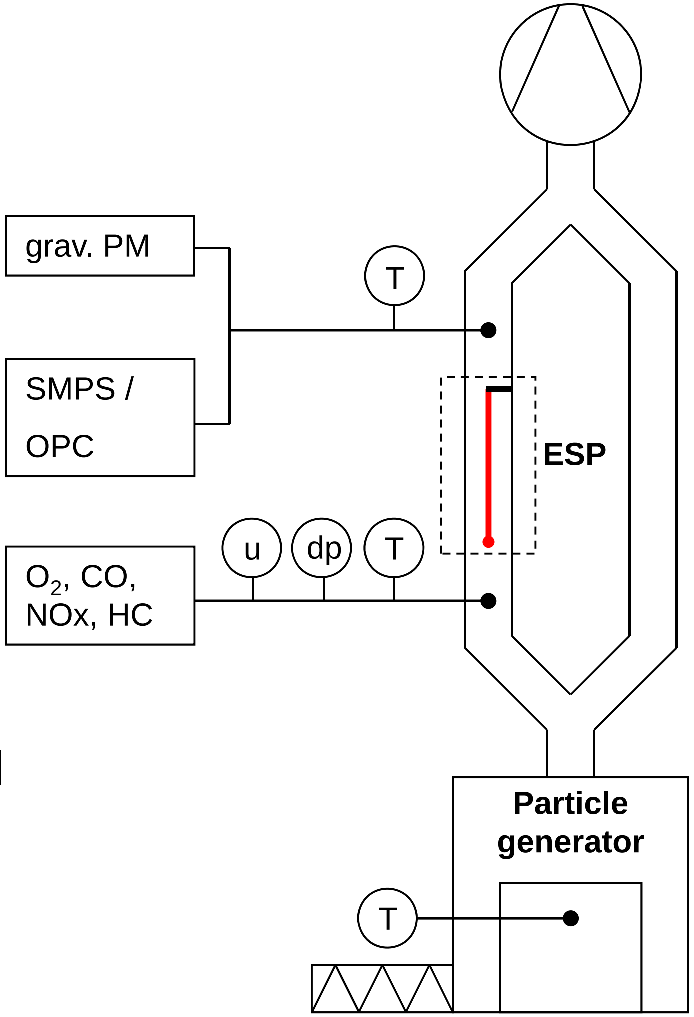
SCA 45 [s/m]

U_{max} -65kV

Particle generator:

pellet boiler modified

Q 15kW



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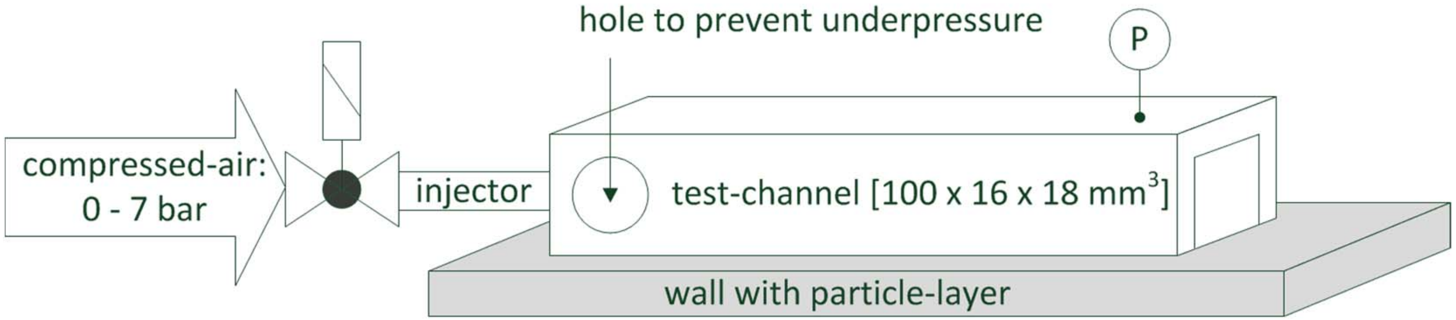
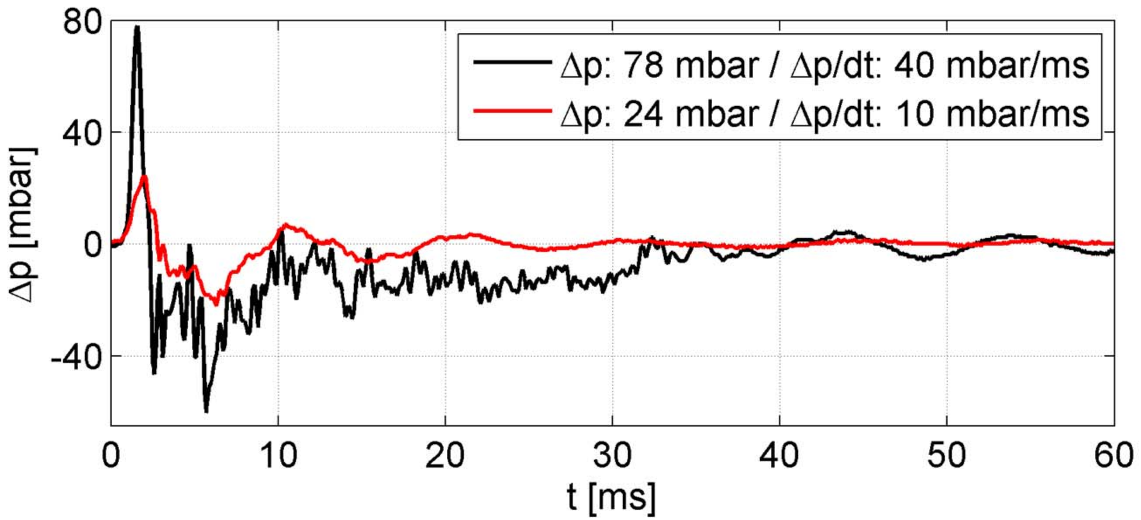
Experimental Setup: 2. Pressure Impulse

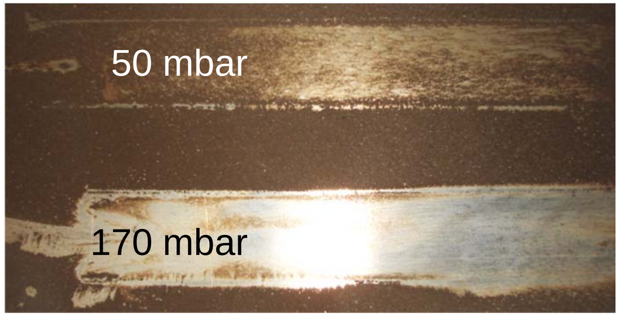
Setup:



Pressure impulse:



Analysis method: optical determination of cleared area: example for COC



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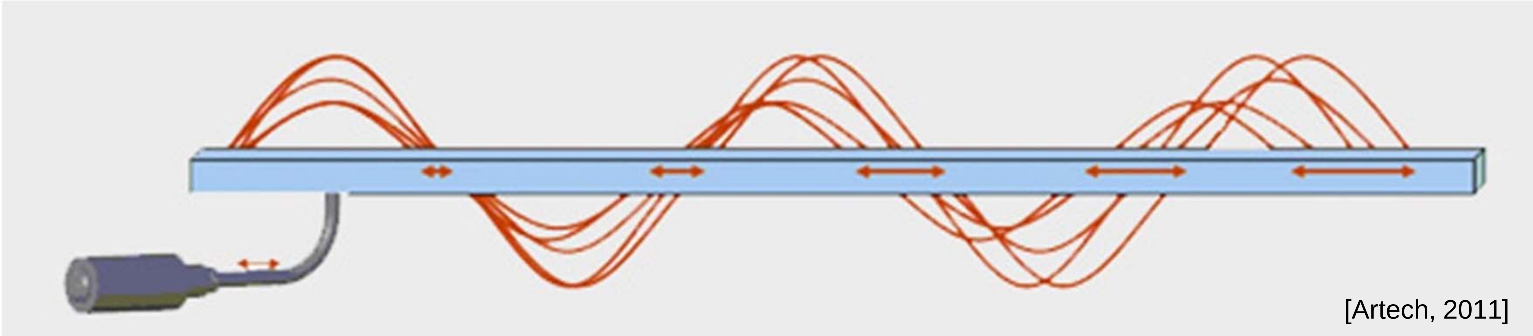
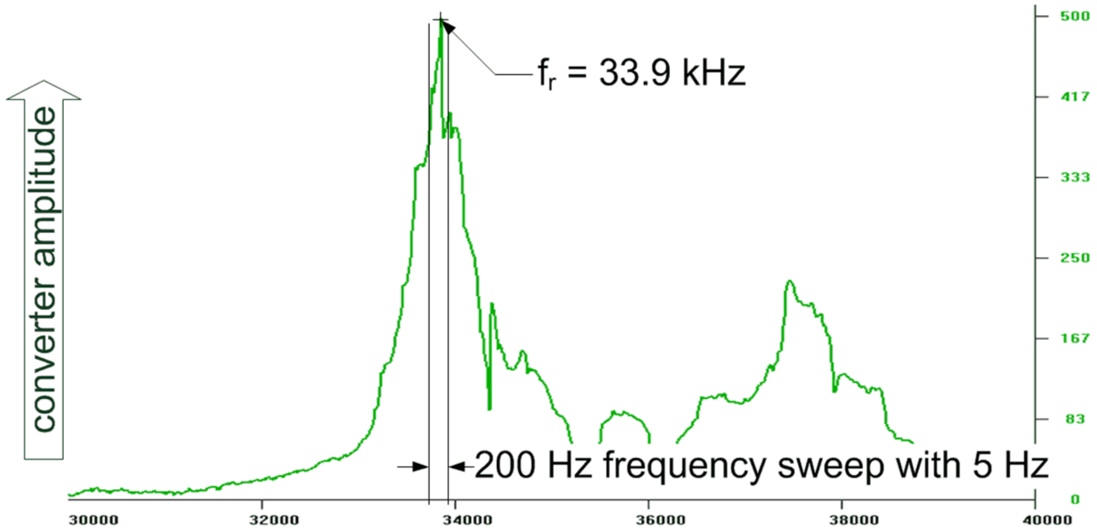
Experimental Setup: 3. Ultrasonic Vibration

Setup:



Acceleration:



Analysis method:

salt and COC: weighting of removed particle agglomerates
soot: optical determination of cleared area

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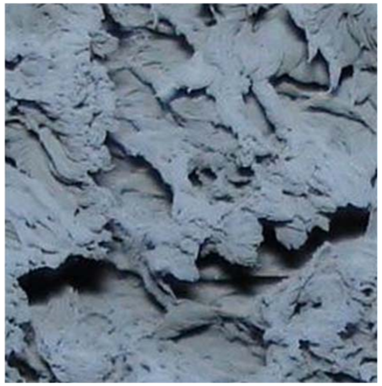

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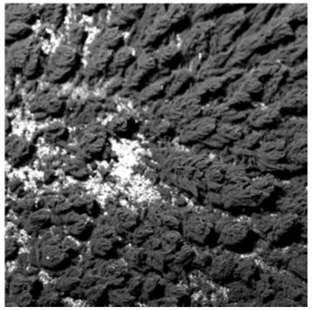
Dust Layer Build-up

Conductive particles:
→'dendritic' build-up

Normal or isolating particles:
→ homogeneous build-up

Soot



Salt

COC

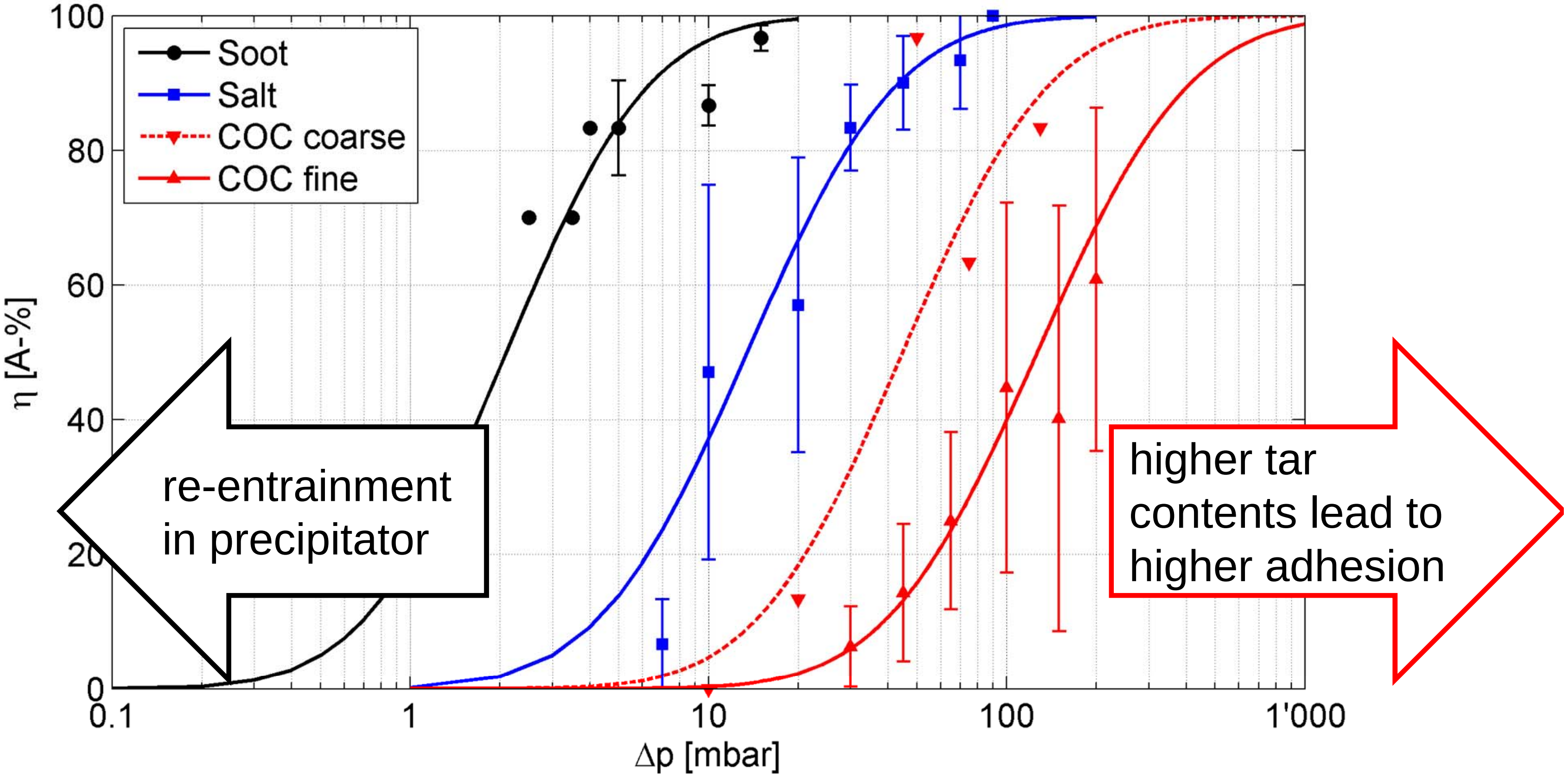
	Soot	Salt	COC
Density ρ_{Solid} [g/cm^3]	1.8 [Römpp, 1992]	KCl: 1.98 [IFA, 2011]	1.1 – 1.3 [IFA, 2011]
Density ρ_{Layer} [g/cm^3]	0.10	1.48	1.0
Porosity ε [%]	94	25	17

→ low contact area reduces adhesion

→ re-entrainment

[Lauber & Nussbaumer, 2009]
[Friess & Yadigaroglu, 2002]

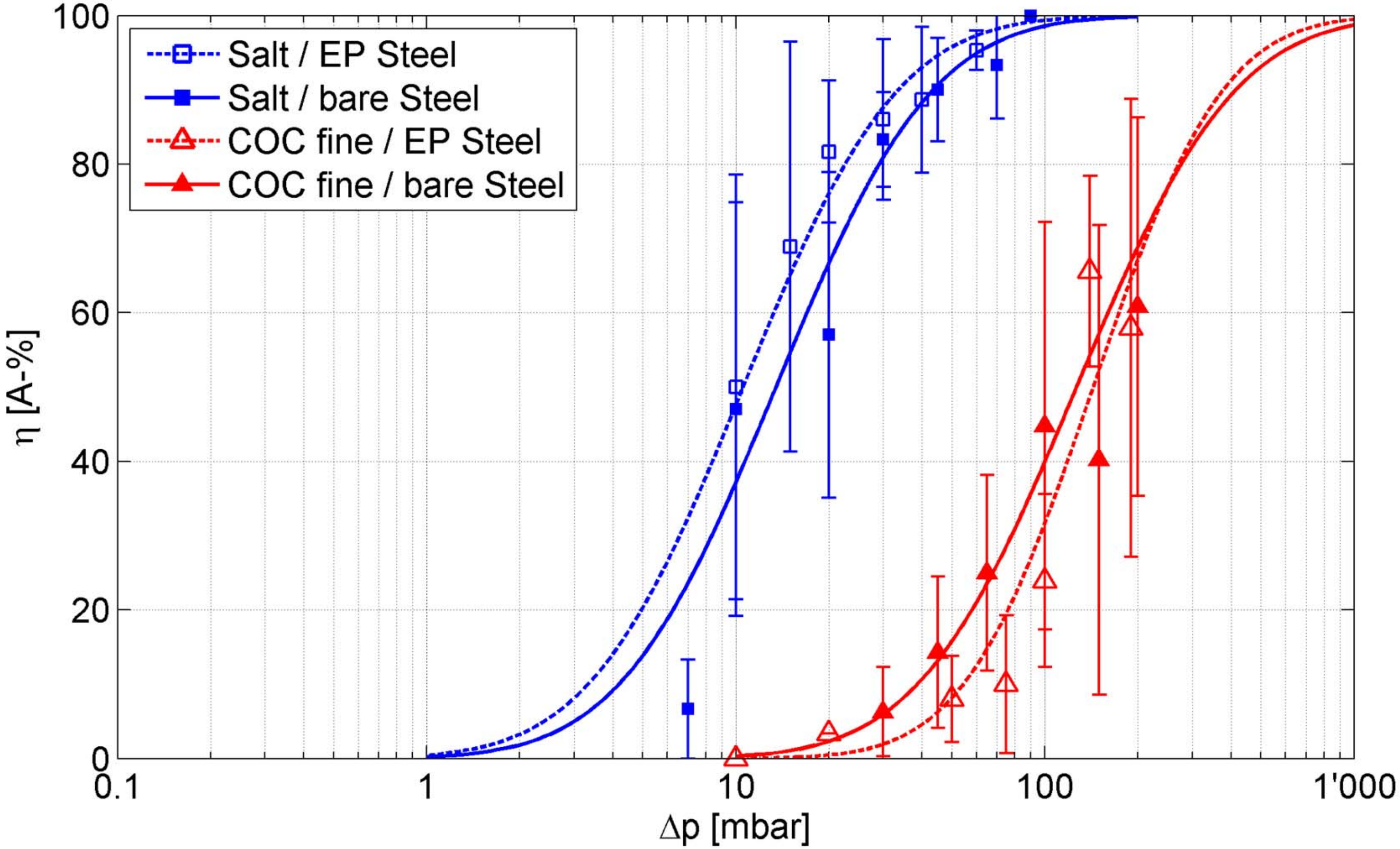
Results of Pressure Impulse



optical sub classification of COC :	Position in ESP [m]	C/H-ratio [mol/mol]
coarse	0 – 0.3	1.56
fine	0.3 – 1	1.19

Results of Pressure Impulse

Influence of Surface: Bare vs. Electro Polished Steel



→ no significant difference observed

Results of Ultrasonic Vibration

	Soot	Salt	COC
Efficiency η at $a \approx 1000 \cdot g$	**25 [a-%]**  (soot: black)	**55 [m-%]**  (salt: dark grey)	**22 [m-%]**  (COC: light brown)
Density ρ_{Layer} [g/cm^3]	0.1	1.48	1.0
Porosity ε	94%	25%	17%
Physical properties	high elasticity & low density	low elasticity & high density	

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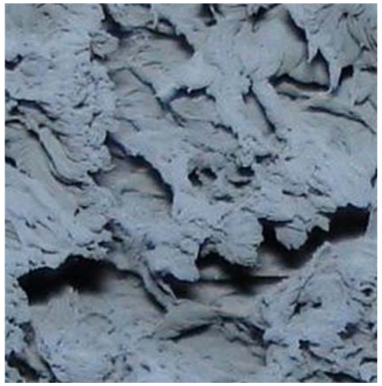

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1. Conclusions on Adhesion

1. Forces needed for dedusting precipitator surfaces depend on adhesion.

2. Adhesion varies more than three orders of magnitude depending on
   - the particle type and
   - the porosity of the particle layer.

3. For soot, the layer build-up in ESP is determined by its high electrical conductivity forming a layer with high porosity and weak adhesion.

4. Salt and COC build a homogenous layer.
   - For salts, van der Waals forces determine the adhesion
   - For COC, liquid compounds significantly increase adhesion.

5. Only minor influences on adhesion are found by
   - Surface roughness and
   - Flue gas humidity (determined by the water content of the fuel).

2. Conclusions on Removal Methods

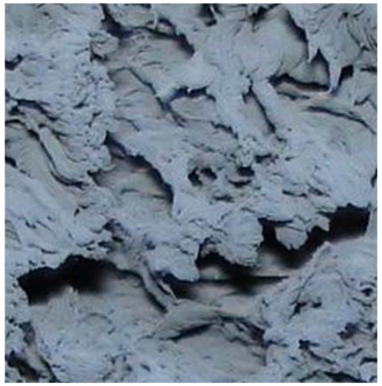
The cleaning effect of aerodynamic drag depends on area (d^2).

The cleaning effect of acceleration depends on mass (d^3) and porosity.

Consequences:

Aerodynamic drag efficiency
decreases from soot (high porosity) to salt and COC (liquids).

Acceleration force is
– suited for salt removal
– but limited for soot (high porosity) and COC (high adhesion)



Acknowledgments

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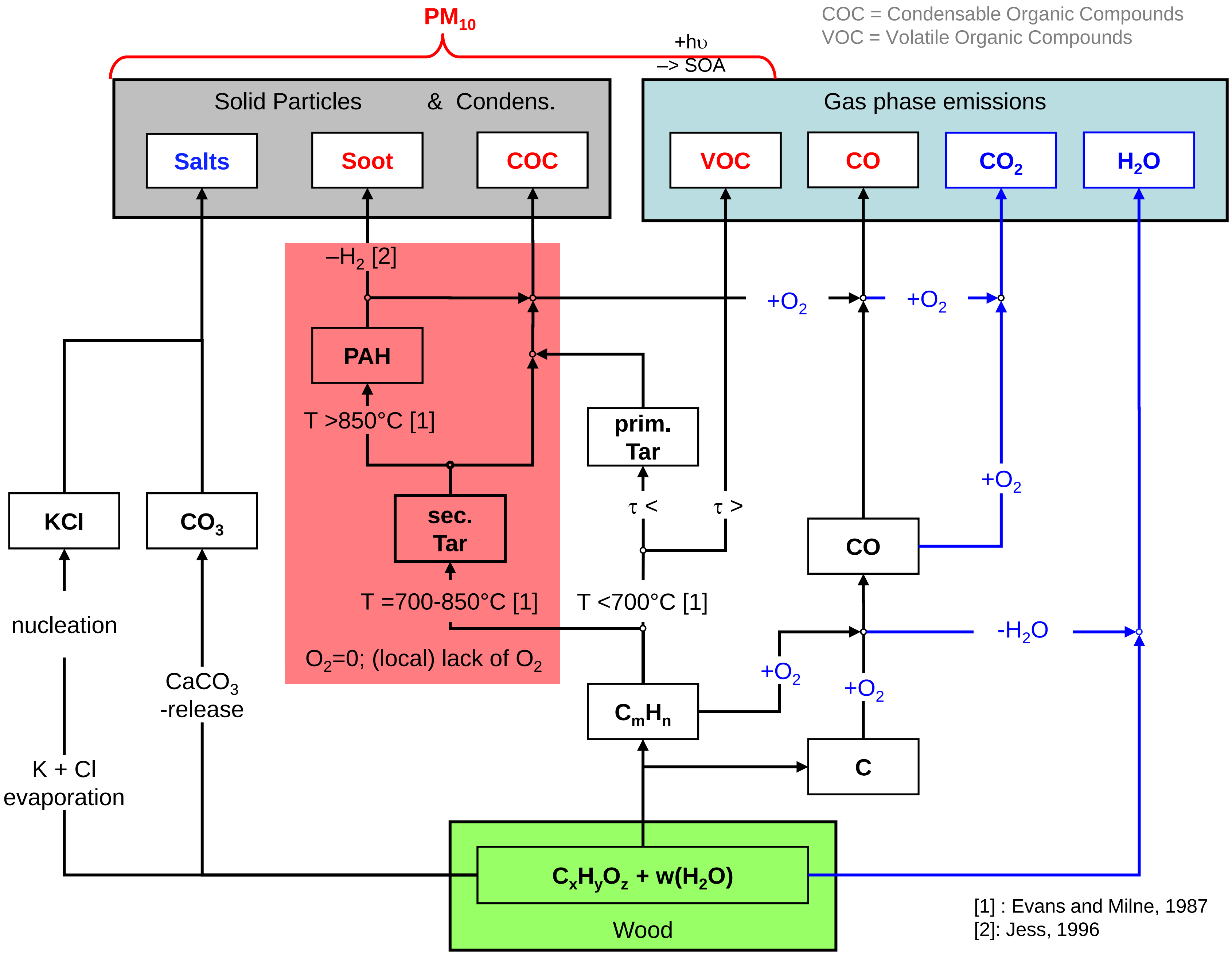
Particle Formation

COC = Condensable Organic Compounds
VOC = Volatile Organic Compounds



[1] : Evans and Milne, 1987
[2]: Jess, 1996

[Lauber & Nussbaumer, 2009]