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SUB-MICRON PARTICLE REMOVAL EFFICIENCY OF ELECTRICALLY ENHANCED WET SCRUBBER

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ABSTRACT

Wet scrubbers are mainly used to remove undesirable gaseous components from flue gases. Normally most scrubbers have low removal efficiency for fine particles. One way to increase the fine particle removal efficiency is to use pre-charging. Particles can be charged by corona discharge like in an electrostatic precipitator.

Charged fine particles are removed by the combined effect of

i. Inertial impaction of particles and droplets
ii. Diffusion of particles to droplets and scrubber walls
iii. Space charge force
iv. Bipolar attraction between particles and droplets
v. Image force attraction between particles and droplets / scrubber walls.

Particles are also agglomerated in the charger in a precipitation / re-entrance process. Resulting large particles are removed in the scrubber by inertial impaction.

Results from laboratory tests, several pilot installations and a full scale (biomass combustion) electrically enhanced scrubber are presented. For fine particles the removal efficiency was observed to be up to 92% for pilot installations and 86% for full scale installation. For pilot installations the removal efficiency depended strongly on particle properties and varied between 65 - 92%.

INTRODUCTION

Concern on the environmental and health effects of fine particles has lead to tightening of pollution control regulations word wide. Many applications that have provided adequate level of particle mass removal are now facing problems with fine and submicron particles. Wet scrubbers that are mainly used for their ability to remove gaseous components from flue gas are also able to efficiently remove particles above 5-10 µm. In many industrial applications this is enough to full fill current emission regulations as most of the particle mass is in the large particles. However scrubbers efficiency on fine particles is typically very low so they will not meet the requirements of new pollution prevention standards.

Wet scrubber installations precipitation efficiency can be increased by additional cleaning devices, like ESP or by using high energy venturi scrubbers. This however would mean a high increase in the initial and/or operational costs for the installation. An alternative way to increase the efficiency is to enhance conventional scrubbers ability to remove fine particles. Our approach is to use electrical charging / agglomeration to increase particle size and capture probability.

ELECTRICAL ENHANCEMENT TECHNIQUES

Several methods to increase wet scrubbers particle removal efficiency with electrical enhancement has been studied and reported over the years (Penney (1941), Kraemer and Johnstone (1955), Klugman and Kosmider (1976), Calvert et al. (1978), Cohen et. al. (1976), Allen (1982), Schmidt and Löffler (1992) and others). The enhancement methods include charging of flue gas particles, scrubbing liquid droplets and the use of external electrical fields. Still only a very few commercially available applications have emerged. Probably the most known is the Ionizing Wet Scrubber (IWS, see www.ceilcoteapc.com) based on Klugmans and Kosmiders work.

ELECTROBOOSTER WET SCRUBBER (EBS)

An electrical enhancement technique called Electrobooster has been developed in co-operation between Tampere University of Technology and Aker Kværner Pulping and Power Division (former Tampella Power, now part of the Metso Corporation). This technique is based on particle charging and agglomeration in a small ESP-like device installed before a wet scrubber. This system is tested in laboratory, in field tests and in full scale pilot installation.

Theory of operation

The enhancement of particle removal in Electrobooster is based on:

i. Agglomeration of fine particles in the ESP section
ii. Space charge precipitation caused by the unipolar charge of particles
iii. Image force attraction between charged particles and neutral droplets/scrubber walls.
iv. Bipolar attraction between charged particles and spray charged droplets

i. Agglomeration in the ESP section

The particle charging unit in the Electrobooster wet scrubber has two functions. It acts as an ESP device with very high flow rate. The charger (booster) is installed in the direction of the gas flow inside the flue gas duct. The flow velocity in the booster is the same as or a little higher than in the duct. Particles are precipitated in the collecting electrodes but because of the high flow the re-entrance rate is also high. The re-entranced particles however are generally larger than 10 µm above witch the precipitation efficiency of a wet scrubbers if practically 100%. So as a first approximation all particles collected in the booster can be considered removed and the collection efficiency for the agglomeration can be estimated by the Deutsch equation.

$$p = 1 - e^{-\left[\frac{wA_c}{M}\right]},$$

where p = particle removal efficiency, w = particle migration velocity, A_c = collector surface area and M = volumetric gas flow rate

The second function of the Electrobooster is that it charges the non-collected particles which is the base for the other particle removal processes.

ii. Space charge precipitation

The particles that are charged in the Electrobooster but not collected by it create a space charge field because of their unipolar charge. This mutually generated field pushes the particles apart and so a fraction of the particles will be precipitated in the walls of the gas duct and in the scrubber. The space charge precipitation efficiency can be calculated using the Deutsch equation where the external field is replaced by the space charge field (Kraemer and Johnstone (1955), Nielsen and Hill (1976))

$$dp = 1 - e^{-\left[\frac{q \cdot e \cdot r \cdot R^2 \cdot C_C \cdot dh}{3 \cdot e_0 \cdot h \cdot d_i \cdot M}\right]},$$

where

p = precipitation efficiency
e = elementary charge
R = precipitator radius
e_0 = vacuum permittivity
d_i = particle diameter
C_C = slip correction factor
q = particle charge
r = space charge density
h = precipitator height
h = gas viscosity
M = volumetric gas flow rate

The space charge density equals particle concentration times the average particle charge. The charge density decreases as the particles get collected and so the differential removal efficiency decreases with the decreasing particle concentration.

iii. Image force attraction

As charged particles approach electrically conducting targets like scrubber liquid droplets or scrubber walls they generate images charges to the target. This is caused by charge separation in the conducting material and makes it act as a charged media. Image force is a short distance force but it increases the effective capture gross section of the collecting media. For scrubbing liquid droplets it can be estimated by the equation:

$$f = \left[\frac{5 \cdot C_C \cdot q_p^{\,2}}{4 \cdot p \cdot h \cdot d_i \cdot w \cdot e_0 \cdot d_d^{\,2}}\right]^{0,4} >> 1,$$

where

Φ = effective gross section C_c = slip correction
q_p = particle charge h = gas viscosity
d_i = particle diameter d_d = droplet diameter
ε_0 = vacuum permittivity
w = relative velocity of particles and droplets

iv. Bipolar attraction between particles and droplets

Scrubbing liquid droplets can became charged in the spraying process. In neutral case some droplets acquire positive charge and same negative charge so that the net charge of all droplets is zero. In Electrobooster scrubber the space charge field of the charged particles can induce opposite charge on the droplets. This phenomenon is a similar to the image charge case. The space charge field causes a charge separation in the liquid being sprayed. If the spraying nozzles are electrically grounded the droplets will all be charged to the opposite polarity of the particles. In this case the particles and the droplets will feel Coulombic attraction. Using modified Deutsch equation we get

$$dp = 1 - e^{-\left[\frac{3 \cdot L \cdot f \cdot w \cdot dh}{2 \cdot M \cdot d_d \cdot v}\right]}$$

and

$$f = -\frac{4 \cdot q_p \cdot q_d \cdot n_d \cdot C_c}{3 \cdot e_0 \cdot p \cdot h \cdot d_i \cdot w},$$

where

d_i = particle diameter η = gas viscosity
q_p = particle charge q_d = droplet charge
p = precipitation efficiency n_d = number of droplets
h = precipitator height v = gas flow rate
M = volumetric gas flow ε_0 = vacuum permittivity
C_C = slip correction
L = volumetric flow of the scrubbing liquid
Φ = effective collection gross section for the droplets
w = relative velocity of particles and droplets
d_d = average droplet diameter

Laboratory scale tests

Laboratory scale tests were used to evaluate the relative efficiency of different precipitation processes. Three different measuring set ups were used. One was specially designed for the estimation of the space charge precipitation (Fig. 1). The second was a small scale preformed spray scrubber with separated diode corona charger unit (Fig. 2). Tests were designed so that it was possible to evaluate the relative efficiency of each process. This was achieved by changing the particle charging conditions, particle concentrations and resident times so that from theoretical basis we enhanced one process and diminished others as much as possible. Third measuring set up was used to evaluate the charge that was induced to the droplets during spraying in external field (Fig. 3).

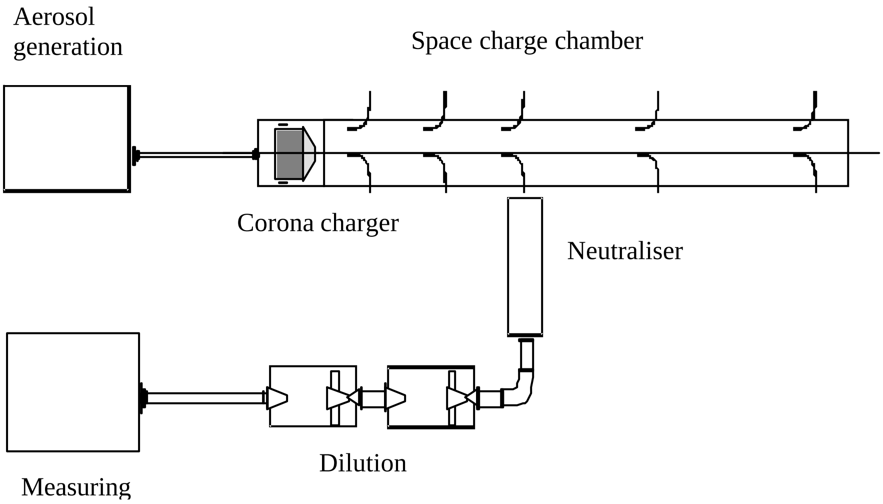

Figure 1. Space charge precipitation efficiency measurement setup. The residence time in the system could be changed by changing flow velocity and/or measurement port.

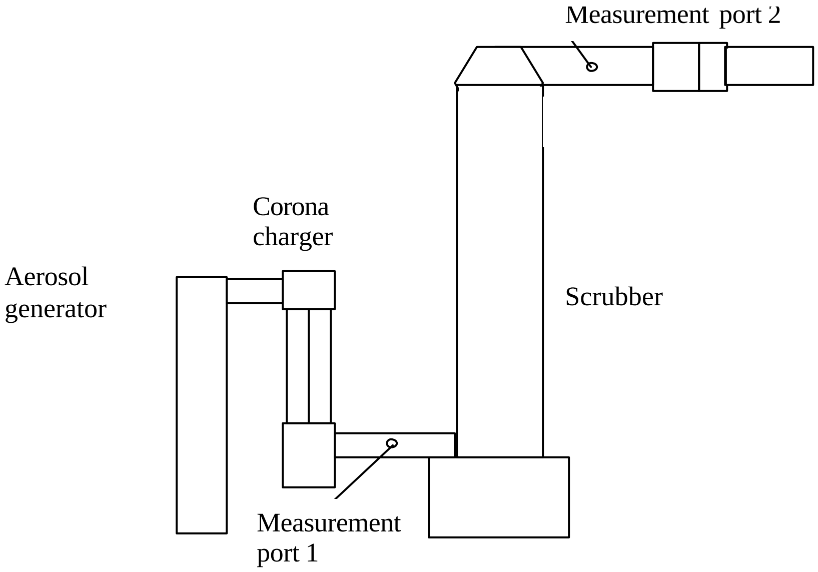

Figure 2. Electrobooster wet scrubber laboratory test setup.

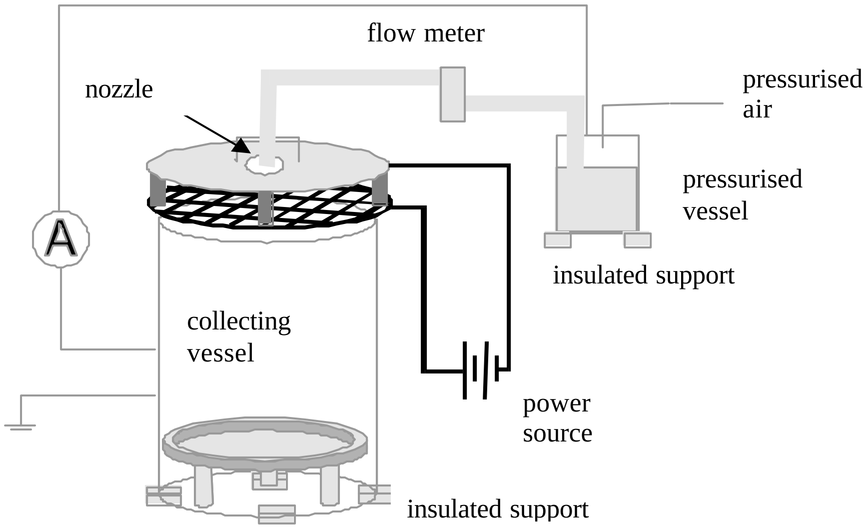

Figure 3. Measurement setup for induced spray charging of droplets.

The results from these measurements are presented in the Fig 4. It shows that particle agglomeration in the charger and space charge precipitation are the dominant processes. The weakness of the bipolar removal is explained by the relatively weak charge state that the droplets achieve in the spraying process (Vaaraslahti et al. (2002)). Image force precipitation is omitted from the Fig 4. as it was zero within the measurement accuracy. The effect of the conventional non-electrical forces is added in the figure for comparison. In the size range of 0.01 to 1 µm it is zero but shows an increasing trend toward the larger particle sizes.

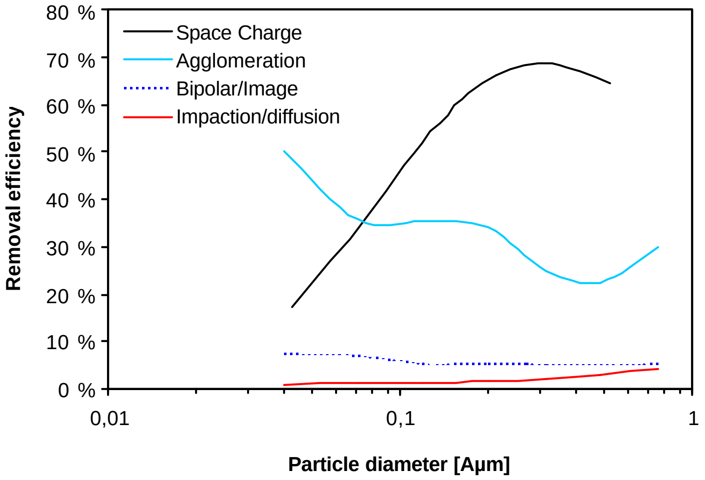

Figure 4. Relative precipitation efficiencies for different particle removal processes. Conventional non-electrical impaction and diffusion processes added for comparison.

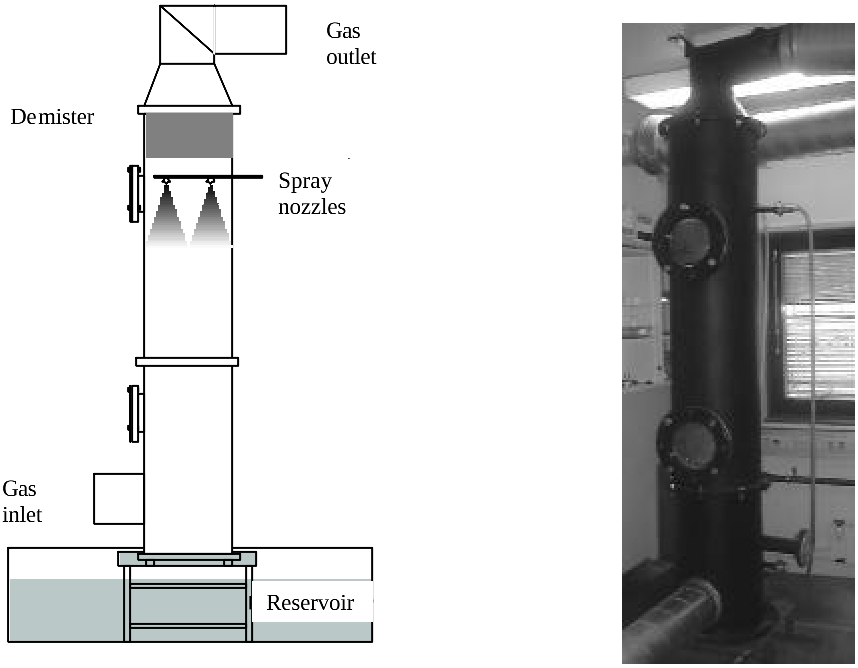

Figure 5. Laboratory scale preformed spray scrubber. Diameter of the scrubber was 400 mm, height 2500 mm. It had 6 spray nozzles (120° full cone nozzles made of PVDF). Gas flow rate was adjustable from 20 to 250 litres per second.

Field tests with Electrobooster Wet Scrubber

Field tests were performed in different industrial applications as presented in Tab. 1. The scrubber was similar to the one used in the laboratory test. Scrubber height was 5500 mm and the upper half was packed. Tab. 1 shows the particle mass loads and particle removal efficiencies in the tests. Compared to the removal efficiency of the wet scrubber itself without electrical enhancement the booster did increased the total precipitation efficiencies from 95% to 99% for peat burning, from 79% to 97% for Peat drying and from 20% to 78% for diesel power engine. The very low collection efficiency (20%) of the non-enhanced wet scrubber with diesel engine is related to the high amount of submicron particles in the diesel exhaust gas.

Table 1. Field test installations and results. All locations in Finland.

Location	**Type**	**Particle load**	**Emission**	**Electrical enhancement (efficiency)**	**electrical efficiency (below 0,5 µm)**
Tampere	Power production, Peat	1400	14 (99 %)	69 ⇒ 14 (80 %)	76 %
Haapavesi	Peat drying	650	27 (97 %)	136 ⇒ 27 (80%)	75 %
Vaasa	Diesel engine	60	13 (78 %)	48 ⇒ 13 (73 %)	60 %
		mg/Nm^3	mg/Nm^3	mg/Nm^3	

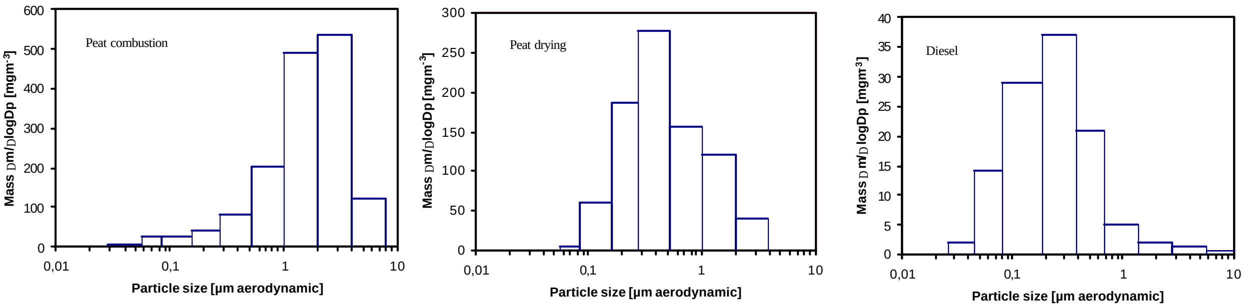

Figure 6. Mass distributions of the different test applications.

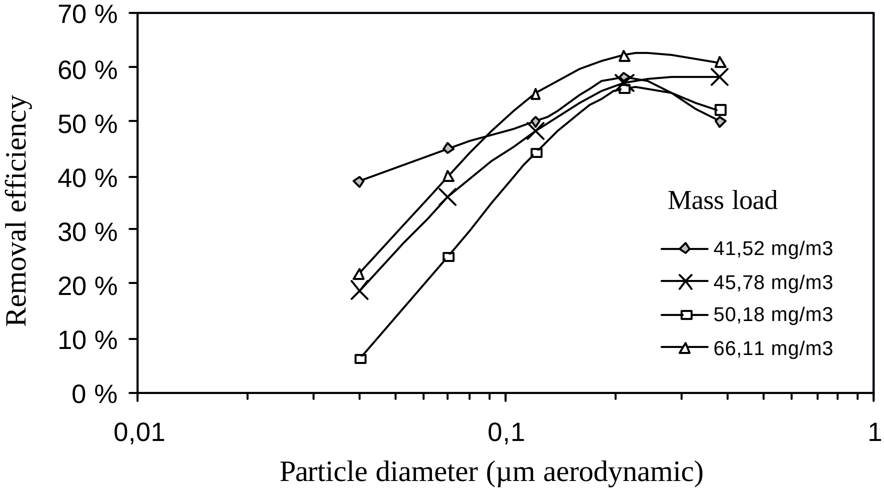

Figure 7. Eletrobooster Wet Scrubbers particle removal efficiency for electrostatic processes (diesel engine). The increasing efficiency with increasing particle load is caused by the increasing space charge effect.

Full scale installation

Booster unit was installed at the biomass combustion power plant located at Savonlinna. It produces 32 MW steam and electrical power for local factory. Flue gases are cleaned by multi-cyclone and by a two stage packed bed wet scrubber. The second stage scrubbing liquid flow is connected to heat exchangers producing additional 10MW of heat for domestic heating at Savonlinna region.

The booster charger was installed inside the gas duct leading to the wet scrubber (Fig. 8). The flow rate at the booster was around 30Nm^{3}s^{-1}, gas temperature 200°C. Relative humidity of the flue gas was between 10 - 20%$_{vol}$ depending on used biomass. The booster used 65 honey combed charger units with rigid emission elements. Each charger unit had a diameter of 18cm and length 80cm. Charger voltage was between 30-50kV$_{PEAK}$ and current from 20 to 50mA$_{AVE}$. The enhanced scrubbers sub-micron particle removal efficiency was increased from 40% to 65%. At the lowest point of efficiency (0.5µm) the efficiency increase was from 13% to 50% (Fig 9.)

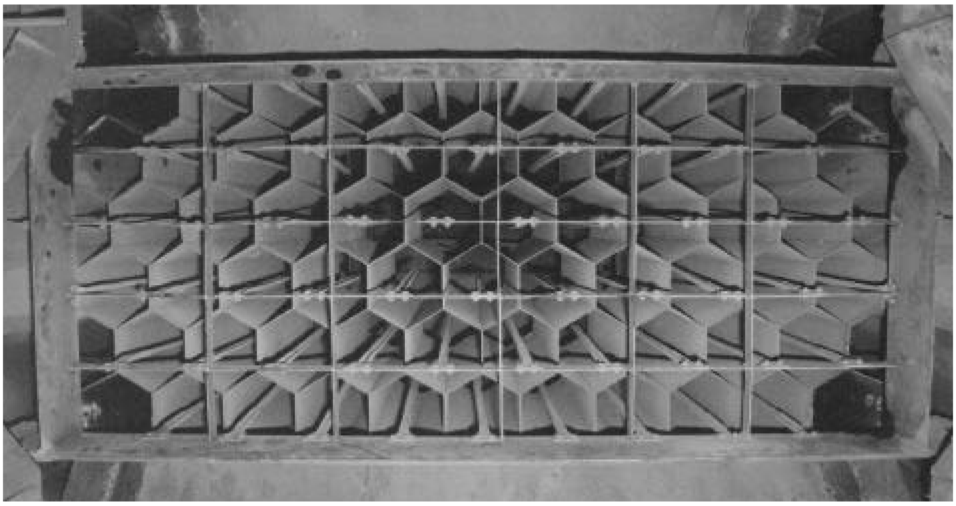

Figure 8. The charger unit (Electrobooster) of the full scale installation.

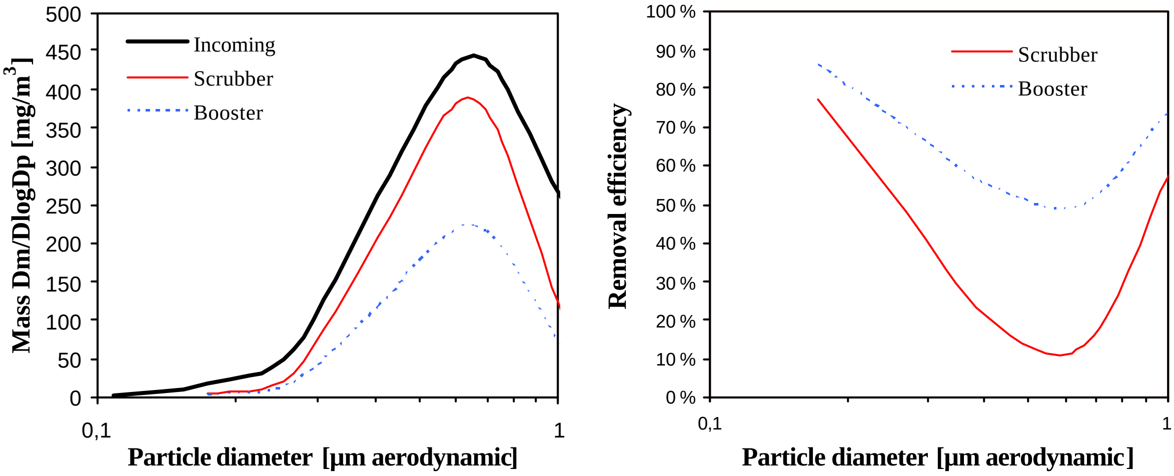

Figure 9. Particle removal efficiency of the full scale installation.

CONCLUSIONS

The study of electrical wet scrubber enhancement technique "Electrobooster Wet Scrubber" or EBS has shown that it is possible to increase the conventional wet scrubbers ability to remove fine and submicron particles. The main phenomena in the EBS are the agglomeration process in the booster unit and space charge effect of the charged particles. The agglomeration increases particle size above 10 µm. Large particles are effectively removed by the wet scrubber. Space charge forces the unipolar particle cloud to expand and part of particles are precipitated in the walls of the flue gas duct and the scrubber vessel. Particles collected in the duct walls agglomerated and they re-enter to the gas flow as large particles which are again easily removed by the scrubber. Bipolar Coulombic attraction and image charge forces play only a minor role in the EBS.

The concept has been tested in laboratory and field test. Full scale installation is also evaluated. It has been shown that depending on the combustion process the efficiency of a conventional wet scrubber can be increased up to 80% compared to non-enhanced case. In the full scale installation in biomass combustion application the overall precipitation efficiency was increased over 40%.

Booster unit can be a low cost solution for cases where new environmental legislations requires better removal efficiency of fine particles than what a conventional wet scrubber can achieve. The devise is small so it can easily be retrofitted in an existing wet scrubber installation. As the booster unit itself is cleaned by re-entrainment in high flow field it does not require any rapping or other cleaning devices. Its power consumption is moderate and it has a low pressure loss. However in applications where the particles are sticky the re-entrainment process may not provide adequate cleaning of the booster and additional cleaning mechanisms are needed. In some cases problems may also rise from the wet scrubbers tendency to generate small particles. If the cleaning liquid has a high concentration of collected material the droplets that escape from the demister may generate even more fine particles than what enter in the scrubber. If this is the case the EBS technology can not decrease the fine particle emissions and a conventional ESP or even a wetESP installed after the scrubber is a better choice.

ACKNOWLEDGMENTS

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