Monitoring of particle separators for emission control of small furnaces. Influences of test set-up and fuel type

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Introduction

The requirements for particle separators to be used in conjunction with biomass furnaces are quite different from those known from HVAC[1], power plants or automotive. High dust loads, very small particles (almost 100% < 1 µm), aggressive atmospheres, high temperatures, long service intervals and a low permissible pressure drop have to be coped with. Furthermore, the expectable sales volume is still limited and altogether tight economic ensues.

Test Setup

The test setup was constructed with the following aims in mind: the precipitator is to be subjected to a flue gas with well characterized dust load, gas composition, temperature and volume flow and the separation efficiency is to be determined by synchronous sampling of raw and clean gas, cf. Fig. 1.

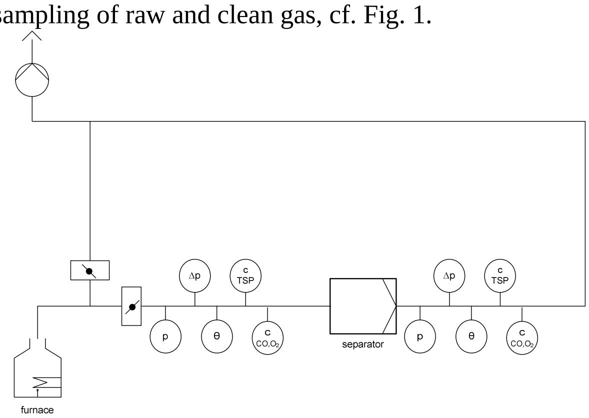

Fig. 1: Process flow diagram of the separator test bed. In order to adjust the volume flow trough the separator, after the furnace the flue gas stream is divided in a part flowing through the separator and a residual stream going straight to the chimney. The flue gas is characterized by draft, flow (Prandtl's Pitot tube), temperature, gas composition and TSP (total suspended particles) are sampled.

Agglomeration and Precipitation

When the dust load and/or the volume flow exceed the capacities of the precipitator, the separation efficiency for some classes of particle diameter may become negative, i.e. the separator seems to produce particles of a certain diameter. This phenomenon is caused by agglomeration. The effects of agglomeration and precipitation were separated by first calculating an agglomeration function based on mass conservation (assuming a constant density), Fig. 2 and then calculating the separation efficiency, Fig 3. The efficiency minimum thus obtained corresponds to literature values. [1,2,3]

[1] Heating, Ventilation, Air Conditioning

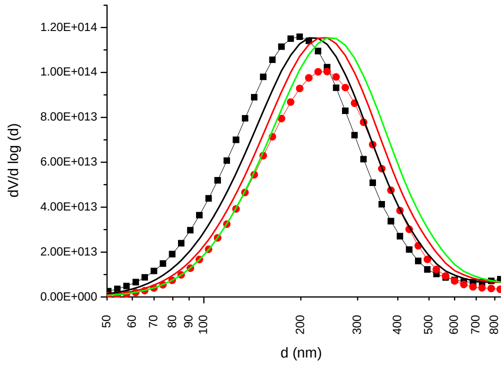

Fig. 2: Volume distribution histogramm for raw (black squares) and clean gas (red circles) together with three possible agglomeration functions (black, red and green lines)

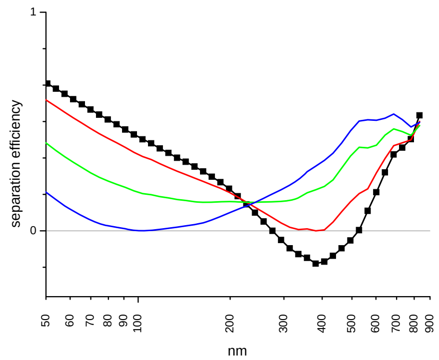

Fig. 3: Separation efficiencies. Black squares: nominal, red line: minimal agglomeration, green line: agglomeration leading to an optimally balanced separation efficiency, blue line: maximum agglomeration. The colours match those of the functions in Fig. 8.

Fuel type

Different fuels and furnaces give rise to different dust compositions, Fig. 4. Potassium is a characteristic component of biomass-derived dust. The composite pellets and the wheat grains produce a dust load with a significant carbon content (grey dust) while straw leads to a high and almost snow-white dust load. Contrary to carbonaceous matter,[4] the inorganic dusts have a low electron affinity. Thus charging of inorganic dust is far less efficient leading to decreased separation efficiency, as shown in Figs. 5 and 6.[5,1,6]

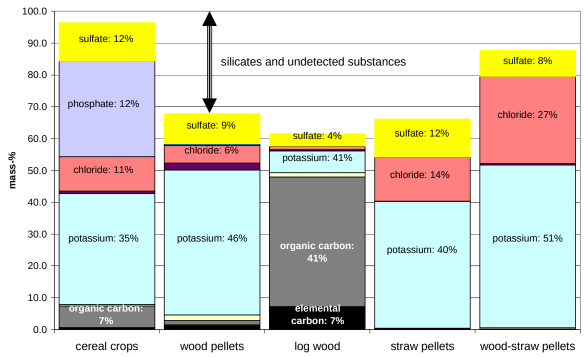

Fig. 4: Composition of dust sampled from furnaces burning different fuels. Dust was sampled on quartz filters, therefore silicates, oxides and hydroxides could not be quantified.

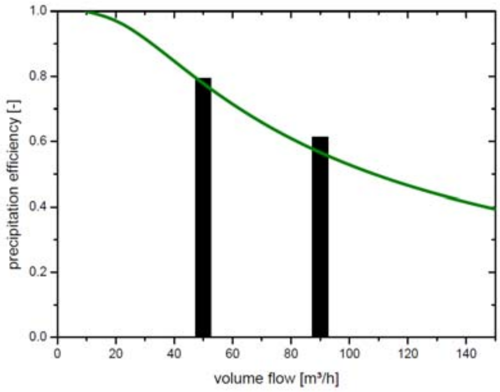

Fig. 5: Separation efficiency of a high-end electrostatic precipitator (bars) vs. its Deutsch-Anderson function. Fuel used: straw-wood composite pellets.

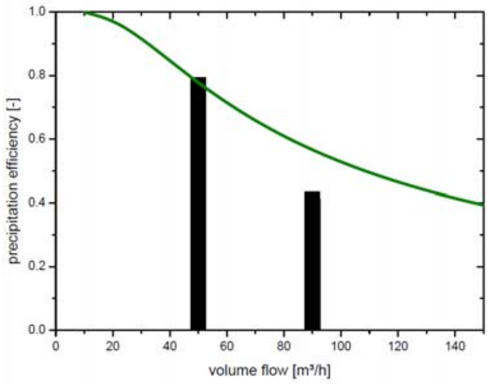

Fig. 6: Separation efficiency of a high-end electrostatic precipitator (bars) vs. its Deutsch-Anderson function. Fuel used: pure straw pellets

$$\eta = 1 - \exp\left(-\frac{Aw_{effective}}{\dot{V}}\right)$$

Eq. [1]: Deutsch-Anderson function. The migration velocity is an effective velocity and as such a function of the precipitator design and the flue gas composition.[2]

Fouling, Reentrainment, and Arcing

Fouling of both electrodes was encountered in this study, abetting reentrainment (anode) and arcing (cathode). Reentrainment may heavily reduce filter performance. This is well known from large scale ESP.[7,8,9] While the arcing itself usually does not harm the precipitator, the ensuing break down of the high-voltage field results in a temporary loss of separation efficiency, repetitive arcing thus compromises the filtration as a whole. The noise associated with arcing, on the other hand is commonly considered unacceptable by the customers.

Conclusion

Large scale separators are known for more than a hundred years. Yet none of the tested separators is mature enough for a continuous unattended operation throughout a heating period. But the market of small scale flue gas dust separators is gaining momentum and new players appear. The DBFZ is prepared for the next round.

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Acknowledgements

Financial support by the Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz is gratefully acknowledged

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DBFZ

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INTRODUCTION

With increasing market shares of biomass combustion units, their particle matter emission is increasingly coming into focus of environmentalists and governmental agencies. In Germany for example, the novelized 1st Federal Imission Protection Ordinance (1. BImSchV, 2010) calls for the installation of emission control measures when non-compliant furnaces are to be used in the future.

The requirements for particle separators to be used in conjunction with biomass furnaces are quite different from those known from HVAC , power plants or automotive. High dust loads, very small particles (almost 100% < 1 µm), aggressive atmospheres, high temperatures, long service intervals and a low permissible pressure drop have to be coped with. Furthermore, the expectable sales volume is still limited and altogether tight economic ensues.

Monitoring and testing of emission control device for small furnaces is an ongoing part of the research program of the DBFZ. In the following some highlights will be presented.

TEST SETUP

The test setup was constructed with the following aims in mind: the precipitator is to be subjected to a flue gas with well characterized dust load, gas composition, temperature and volume flow and the separation efficiency is to be determined by synchronous sampling of raw and clean gas. The result is a design with two measuring sections dimensioned in accordance with the requirements of VDI 2066 Part 1 and DIN 4702 Part 2, i.e. with an inner diameter of 77 mm and 1.5 m length, equipped with several ½ " feed pipes for gas analysis and SMPS sampling and a 2½" port for the isokinetic sampling each, one up- and one downstream of the precipitator. In order to allow an independent operation of the furnace and to provide an adjustable volume flow through the separator a bypass is included between furnace and separator test bed, cf. Fig. 1.

The main point of critic concerning the presented test-bed design is associated with the altering of flue gas conditions due to the raw gas measuring section. The extremely high particle number concentrations encountered in solid fuel combustion lead to significant agglomeration processes within short residence times. Non-ideal thermal insulation leads to cooling of the flue gas. Thermophoretic precipitation and condensation of tar on the particles as well as reentrainment of debris may occur. On the asset side are: (i) the possibility to test every type of filter, not only those that may be switched on and off, (ii) little influence due to non-stationary combustion conditions (stoves!) since raw and clean gas are measured concurrently, (iii) detection of dilution caused by false air, and (iv) shorter experiment time since two samples (raw and clean) are taken at once.

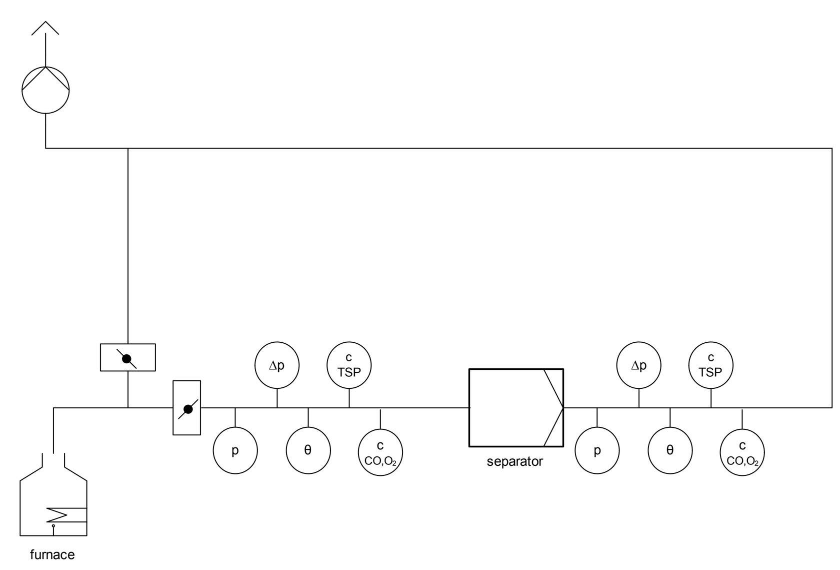

Fig. 1: Process flow diagram of the separator test bed. After the furnace the flue gas stream is divided in a part flowing through the separator and a residual stream going straight to the chimney. The flue gas is characterized by draft, flow (Prandtl's Pitot tube), temperature, gas composition and TSP (total suspended particles) are sampled.

AGGLOMERATION AND PRECIPITATION

When the dust load and/or the volume flow exceed the capacities of the precipitator, the separation efficiency for some classes of particle diameter may become negative, i.e. the separator seems to produce particles of a certain diameter. Quite obviously, this phenomenon is caused by agglomeration. In order to come up with a more realistic description, the effects of agglomeration and precipitation were separated by first calculating an agglomeration function based on mass conservation (assuming a constant density), Fig. 8 and then calculating the separation efficiency, Fig 9. The efficiency minimum thus obtained corresponds to literature values.[1,2,3]

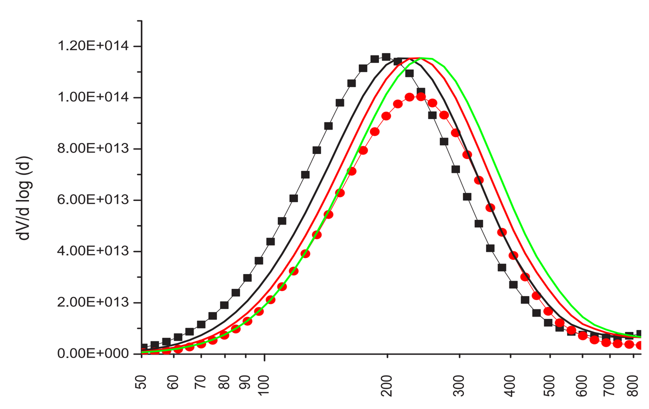

Fig. 8: Volume distribution histogramm for raw (black squares) and clean gas (red circles) together with three possible agglomeration functions (black, red and green lines)

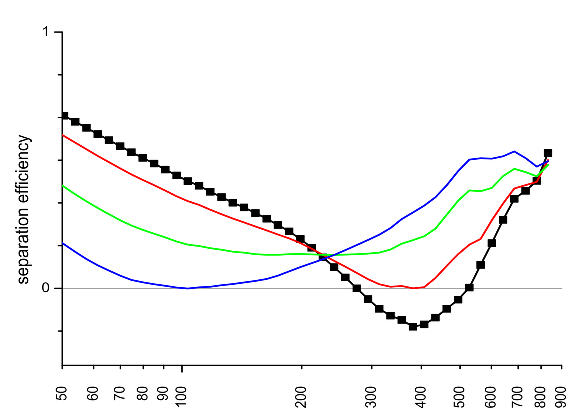

Fig. 9: Separation efficiencies. Black squares: nominal, red line: minimal agglomeration, green line: agglomeration leading to an optimally balanced separation efficiency, blue line: maximum agglomeration. The colours match those of the functions in Fig. 8.

FUEL TYPE

Different fuels and furnaces give rise to different dust compositions, Fig. 2. Potassium chloride is the characteristic component of biomass-derived dust. Quite striking is the difference in carbonaceous matter in the dust between automated furnaces and log wood stoves. The composite pellets and the wheat grains produce a dust load with a significant carbon content (grey dust) while straw leads to a high and almost snow-white dust load. Contrary to carbonaceous matter,4 the inorganic dusts have a low electron affinity. Thus charging of inorganic dust is far less efficient leading to decreased separation efficiency.[5,1,6]

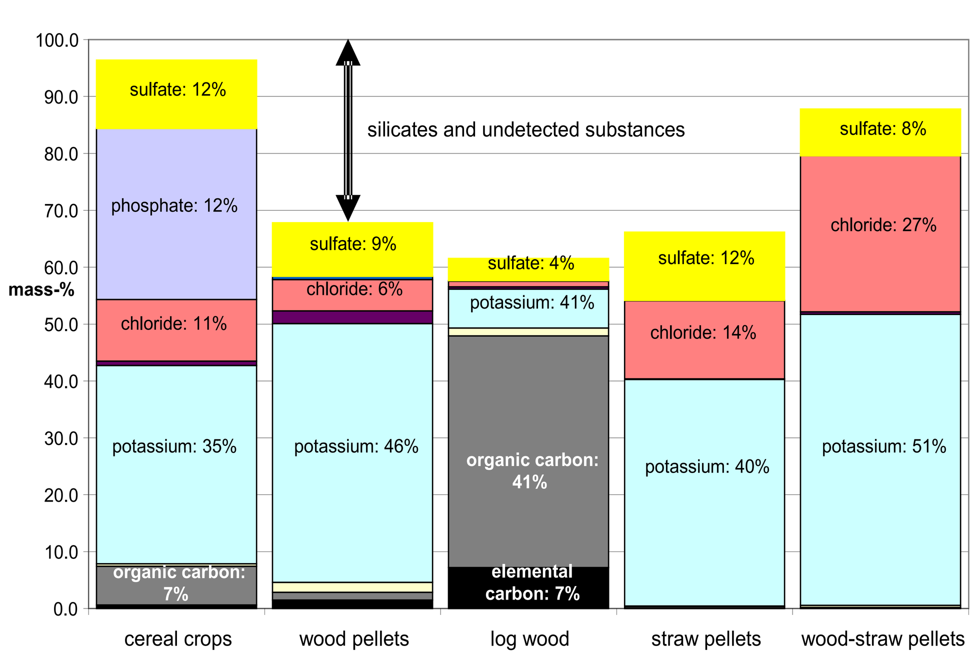

Fig. 2: Composition of dust sampled from furnaces burning different fuels. The values for calcium, nitrogen, and zinc (between organic carbon and potassium, between potassium and chloride and between chloride and phosphorus respectively) are too small to be significant in this display. Dust was sampled on quartz filters, therefore silicates, oxides and hydroxides could not be quantified.

FURNACES

The furnaces used in this study may be classified as wood pellet boilers, stoves and multi-fuel boilers. Wood pellet boilers are the least cumbersome, since they run steady and reproducibly producing very fine particles with a low dust load and reasonable electron affinity, but their low emissions may not require an end-of-pipe particle filter. To operate a stove in a reproducible manner requires standardized fuels and good craftsmanship. Even with elaborate firing procedures the question remains whether and how to include the ignition and burn-off phases. For lack of a scientifically sound criterion the ignition phase is considered completed after 3 min, as defined by DIN EN 13240.

Multi-fuel boilers capable of utilizing wood chips and pelletized agrofuels play an important role in the development of agrofuels and pave the road to specialized agrofuel boilers. With their focus on operational availability – agrofuels tend to slag formation – multi fuel boilers show high dust loads and not seldom rapid fluctuations in combustion quality. The low prices of agrofuels in combination with the legal situation in Germany create an attractive niche for multi-fuel boilers with integrated particle separators. The separation efficiencies measured for particle filters in conjunction with multi-fuel boilers are in general lower than those of wood pellet boilers, cf. the following chapters.

SEPARATOR DESIGNS

There are a number of conceivable designs for particle separators. Yet, the only separators for small furnaces < 50 kW that have emerged on the market and do show a net separation efficiency are electrostatic precipitators (ESP). That's why in the following only those will be considered.

VOLUME FLOW

While there is a wealth of more elaborate efficiency equations derived from theoretical modeling of electrostatic precipitation, without any knowledge about the insides of a commercial "black box" precipitator the classical semi-empirical Deutsch-Anderson function (Eq. [1]) is what one is left with.[2]

In this study the same precipitator was subjected to flue gas derived from burning straw-wood composite pellets (Fig. 4) wheat grains (not shown, almost identical to Fig 4) and pure straw pellets (Fig 5).Under these conditions the limiting factor changes from precipitation area to charging efficiency. While at the layout volume flow of 50 m³/h the residence time still suffices to effectively charge even straw-derived flue gas particles, at higher flow rates this is no longer the case (Fig. 5).[7,8,3,9]

$$\eta = 1 - \exp\left(- \frac{A w_{effective}}{\dot{V}} \right)$$

Eq. [1]: Deutsch-Anderson function. The migration velocity is an effective velocity and as such a function of the precipitator design and the flue gas composition.[2]

DUST COLLECTION AND REENTRAINMENT

The precipitated dust forms very loose layers that are easily dispersed back into the gas stream if they are not effectively removed. None of the tested precipitators had an effective hopper system; all of them suffer reentrainment upon rapping during operation of the furnace, i.e. with a flue gas stream passing through the precipitator. The phenomenon itself is well known from large scale ESP.9,10,11 The quantitative measurement of this type of reentrainment requires a time-resolved wide-range particle monitor which was not available when the experiments were performed.

FOULING AND ARCING

Problems connected with fouling of both electrodes were encountered during the experiments. After runs with the stove, rigid incrustations were found on the cathode and its insulators, Fig 6. The cathode is purged by a slow, continuous air stream. Supposedly, sticky organic compounds from incomplete combustion act here as glue between the particles resulting in failure of the purging mechanism.

After exposing the precipitators with flue gases from agrofuel combustion, the high dust loads lead to complete surface coverage of electrodes and insulators with salty dust. These coatings may be conductive enough to bridge the insulators and thus lead to failure of the high voltage supply.

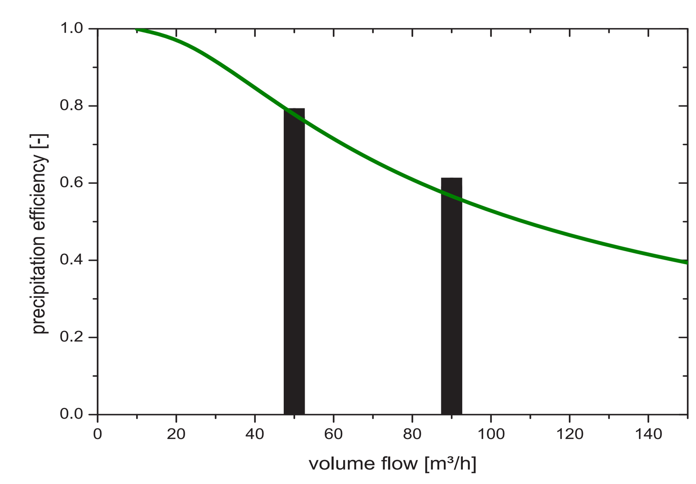

Fig. 4: Separation efficiency of a high-end electrostatic precipitator (bars) vs. its Deutsch-Anderson function. Fuel used: straw-wood composite pellets

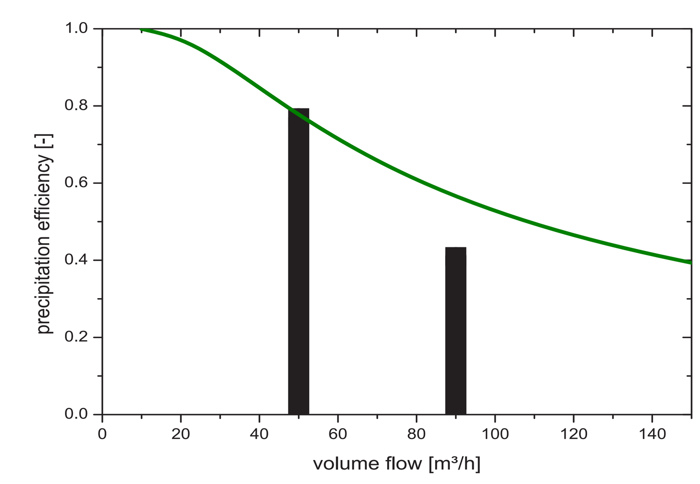

Fig. 5: Separation efficiency of a high-end electrostatic precipitator (bars) vs. its Deutsch-Anderson function. Fuel used: pure straw pellets.

Arcing is a phenomenon often encountered with high voltage applications. While the arcing itself usually does not harm the precipitator, the ensuing break down of the high-voltage field results in a temporary loss of separation efficiency, repetitive arcing thus compromises the filtration as a whole. The noise associated with arcing, on the other hand is commonly, considered unacceptable by the customers since especially stoves are operated in very noise-sensitive circumstances (living room).

CONCLUSION

Large scale separators are known for more than a hundred years. Yet none of the tested separators is mature enough for a continuous unattended operation throughout a heating period. But the market of small scale flue gas dust separators is gaining momentum and new players appear. The DBFZ is prepared for the next round.

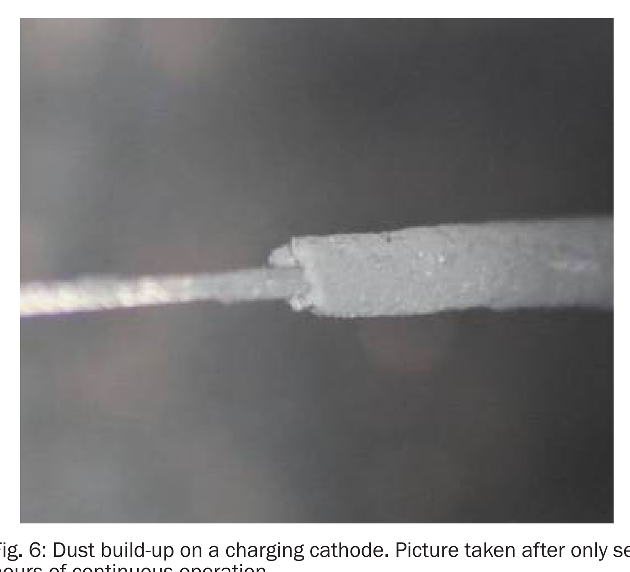

Fig. 6: Dust build-up on a charging cathode. Picture taken after only several hours of continuous operation.

Fig. 7: Fouling of the flue gas duct – here the measuring section. Picture taken after only several hours of continuous operation.

ACKNOWLEDGEMENTS

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