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

Justus von Sonntag*, Tobias Ulbricht

Introduction
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.

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.

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

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
Fuel used:

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

\[
\eta = 1 - \exp\left(-\frac{A\nu_{\text{effective}}}{V}\right)
\]

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.²³⁵ 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.

Literature


Acknowledgements

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

Part of the research was performed in cooperation and co-financed by EIFER
One of the precipitators scrutinized was provided by the Karlsruhe Institute of Technology KIT
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to furnace and to provide an adjustable volume flow through the separator a bypass is included between furnace and separa-
tester bed, cf. Fig. 1.
The main part of critic concerning the presented test-bed design is associated with the altering of flue gas conditions
due to raw-gas-measuring section. The extremely high particle number concentrations encountered in solid fuel com-
bustion 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 gas on the particles as well as reentrainment of
dusts 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 (steady) since raw and clean gas are mea-
sured concurrently, (iii) dilution caused by false air, and (iv) shorter experiment time since two samples (raw and clean) are taken at once.

AGGLOMERATION AND PRECIPITATION
When the dust load and the volume flow exceed the capacities of the precipitator, the separation efficiency for some
classes of particle diameters 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 achievable 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

FUEL TYPE
Different fuels and furnaces give rise to different dust compositions, Fig. 2. Potassium chloride is the characteristic comp-
ponent 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 light and almost snow-white dust load. Contrary to carbonaceous matter the
inorganic dusts have a low electron affinity. Thus charging of inorganic dust is far less efficient leading to decreased
separation efficiencies.1,2,3

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 combustion, since they run steadily and reproducibly producing very fine particles with a low
load and reasonable electron affinity, but their low emissions may not require an end-of-pipe particle filter. To
operation in a reproducible manner requires standardized fuels and good craftsmanship. Even with elaborate
fireplace questions the presentement whether and how to include the ignition and burn-off phases. For lack of a sci-
centric sound criterion the presentement is completed after 3 min, as defined by DN EN 13240. Multi-fuel boilers capable of utilizing wood chips and pelleted agglomerates play an important role in the development
agglomerates and the road to specialized agglomerated fuels, with more focus on operational availability – agglomerates
tend to sag formation – multi-fuel boilers show high dust loads and not seldom rapid fluctuations in combustion qua-
lity. The low prices of agglomerates in combination with the legal situation in Germany create an attractive side for
multi-fuel boilers with integrated particle separators. The separation efficiencies measured for particle filters in conjunc-
tion 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 ≤ 5 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 these will be considered.

VOLUME FLOW
While there is a wealth of more elaborate efficiency equations derived from theoretical modeling of electrostatic pre-
cipitation, without any knowledge about the inside of a commercial “black box” precipitator the classical semi-empiri-
cal Deutsch-Anderson function (Eq. (1)) is what one is left with.

\[
\eta = 1 - \exp \left( -\frac{\text{effective } V}{\text{critical Deutsch-Anderson function}} \right)
\]

In this study the same precipitator was subjected to flue gas derived from burning straw-wood composite pellets (Fig.
4) wheat grain (not shown, almost identical to Fig. 4) and pure straw pellets (Fig. 5). Under these conditions the limi-
ting factor changes from precipitation area to charging efficiency. While at the plant volume flow of 50 m³/h the resi-
dence time still suffices to effectively charge even straw-derived flue gas dust. For higher flow rates this is no lon-
ger the case (Fig. 5).4,5

DUST COLLECTION AND REENTRAINMENT
The precipitated dust forms very loose layers that are easily dispersed back into the gas stream if they are not ef-
fectively removed. None of the tested precipitators had an effective hopper system; all of them suffer reentrainment
upon re-entraining during operation of the furnace, i.e. with a dust stream passing through the precipitator, even
itself is well known from large scale ESPS,0,11 The quantitative measurement of this type of reentrainment requires a time-averaged wide-range particle monitor which was not available when the experiments were performed.

FOILING AND ARCING
Problems connected with fouling of both electrodes were encountered during the experiments. After runs with the
stove, the electrodes were found on the cathode and its insulators. Fig. 6. The cathode is purged by a slow, conti-
uous air stream. Supposedly, sticky organic compounds from incomplete combustion act as glue between the
particles resulting in failure of the purging mechanism. After exposing the precipitators with flue gasses from agrofuel combustion, the high dust loads lead to complete sur-
facing 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.2

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 ef-
ciciency, 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 nois-
sitive circumstances (living room).

CONCLUSION
Large particle 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 separa-
tors is gaining momentum and new players appear. The DBFZ is prepared for the next round.

LITERATURE
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Deutsches BiomasseForschungsZentrum DBFZ