Electrostatic agglomeration and centrifugal separation of diesel soot particles

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Abstract

For the collection of diesel soot particles, a two-stage collection system is employed consisting of a cyclone in combination with a preceding electrostatic agglomerator. By virtue of its design, the agglomerator is, in principle, a tubular electrostatic precipitator. The agglomeration mechanism is based on the fact that the electrically conductive soot particles accumulate at the collecting electrode of the agglomerator as flake-like structures. These are re-entrained when they exceed a certain size. The process of agglomeration can therefore be divided into three steps, i.e. particle transport, formation of agglomerates and emission. In order to assess the efficiency of the agglomerator, a measuring methodology has been developed which allows the determination of the size distribution of the soot particles over the range 17 nm to 40 μm. Investigations carried out in connection with this work show that the proportion of particles bound in agglomerates depends essentially upon the operating level of the engine. Depending on the various conditions employed, more than 90% of the particle mass may be bound in agglomerates whose sizes exceed 3 μm. With increasing engine load, the proportion of agglomerates decreases to ca. 40%. Varying the gas volume flow at a constant engine operating level demonstrates that such a dependency on load is not related to residence time, i.e. low efficiency does not arise from insufficient particle transport, but appears to be associated with one of the subsequent stages of the agglomeration process. Details of these processes have not been investigated so far. The total collection efficiency achieved via this system varies between 43% and 87% according to the various operating states of the engine. This significant difference can be explained in terms of the dependence of agglomeration and agglomerate collection upon engine load and speed.

Keywords: Electrostatic agglomeration; Centrifugal separation; Diesel soot particles; Cyclone

1. Introduction

To date no arrangement exists for the collection of diesel soot particles which is applicable in series production. The requirements to be met by such a collector before it can be used in a motor vehicle are maximum reliability, cost efficient design and stable behaviour in long-term operation. For quite some time, deep-bed ceramic filters have been favoured for this kind of application. Although such filters are distinguished by a high collection efficiency, they are not designed to endure the thermal and mechanical strains arising during vehicle operation [1]. On comparing other collectors which may be considered as possible alternatives, it is found that the cyclone has certain advantages for motor vehicle application. Thanks to its simple and robust design, it can be manufactured in a cost-effective manner, it is reliable in operation and can be exposed to temperatures exceeding 1000 °C. These advantages may be contrasted with the comparatively low collection efficiency of the cyclone. Thus, even high-performance cyclones demonstrate unsatisfactory results in the submicron range in terms of collection efficiency. When it is considered that with diesel soot ca. 80% of the particle mass lies in this range, the use of a cyclone is only promising if the mean particle size can be increased by the addition of an efficient agglomeration phase.

The Bosch company was the first to report such a procedure, involving the use of a cyclone in combination with a preceding electrostatic agglomerator [2].
The high electrical conductivity of soot particles enables agglomeration to be readily induced in an electrostatic precipitator. In association with the succeeding cyclone, this provides a compact collecting system capable of enduring the strains arising during the operation of a vehicle. The total collection efficiency achievable with this system depends on the efficiency of the agglomerator as well as on the extent to which efficient collection of agglomerates within the cyclone occurs. In stationary experiments values of between 60% and 90% were obtained, the results being clearly influenced by the operating level of the diesel engine [2]. To date, no findings are available which show the extent to which the size distribution of the soot particles is modified by the agglomerator, i.e. what proportion of the primary particles is bound in agglomerates and how the size distribution of the agglomerates may be characterised in terms of the geometric and operational parameters.

It is the object of this paper to illustrate the efficiency of an agglomerator for various operating states and to determine the influence of various fundamental parameters. A precondition of the experiments undertaken was the development of a suitable measuring methodology which, even under difficult marginal conditions, would enable complete coverage of the particle size distribution.

2. Experimental details

Investigations concerning the agglomerator were carried out under practical conditions using an engine test bench whose schematic design is shown in Fig. 1. The essential components of this arrangement are the diesel engine with a fuel supply and a cooling circuit, the exhaust system with agglomerator and cyclone, and the measuring system with a dilution tunnel.

As a soot generator, a turbo-diesel engine equipped with an oxidation-type catalytic converter as by VW was used. This motor has been available commercially since 1992 in cars such as the Rabbit and the Passat. It had a capacity of 1900 cm³ and an engine power of 55 kW. The engine load could be varied through the use of a hydrodynamic brake. The thermal energy produced by the engine was dissipated via a controlled tubular heat exchanger. The motor was operated with conventional diesel fuel.

The design of the electrostatic agglomerator is shown in Fig. 2. This device basically consisted of a tubular electrostatic precipitator with a cylindrical collecting electrode. Although the tangential gas inlet and outlet generated a vortex flow inside the agglomerator, this was not a precondition for the functioning of the apparatus. The axially mounted corona discharge electrode was furnished with 28 discharge disks whose shape was as shown in Fig. 3. When a voltage above the so-called corona onset voltage was fed to the disk, electrical charges were released at the tips of the discharge electrode. Due to the large number of tips and the resulting high current density, charging of the particles was complete within a few milliseconds. With a mean residence time of over 70 ms, it may be assumed that the particles attained almost saturation charge.
Fig. 4. The geometry of the cyclone employed.

The dimensions of the cyclone employed in the experimental set-up are shown in Fig. 4. Due to its small size, unusually high inflow speeds of up to 50 m s\(^{-1}\) were achieved in this case. The apex cone mounted in the dust discharge opening of the cyclone had a stabilising effect on the vortex and prevented re-entrainment of the collected particles. The use of a dust hopper for intermediate storage of the collected particles was not necessary since they are removed continuously with a partial gas flow.

Measurement of the particle size distribution and concentration behind the agglomerator or cyclone was achieved via a DMPS system manufactured by TSI, in conjunction with a light scattering analyser with an optically defined measuring volume, developed and manufactured at the Institut für Mechanische Verfahrenstechnik und Mechanik \[3, 4\]. The accessible range of particle sizes was between 17 nm and 698 nm for the DMPS system, and between 640 nm and 40 \(\mu\)m for the light scattering analyser. Thus, the range of sizes covered by the two combined devices comprised more than \(10^3\). Sampling of partial flow necessary for size analysis is undertaken by means of two heated isokinetic sampling probes. After sampling, the exhaust gas was diluted with purified ambient air. Such dilution was necessary for two reasons. Firstly, the temperature of the exhaust gas had to be brought down to a sufficiently low value to ensure that the measuring devices were not damaged on condensation processes. Secondly, the high particle concentrations prevailing in the undiluted exhaust gas could have caused errors in the light scattering analysis.

An important advantage of the DMPS system is that no calibration is required and that by the use of this method spherical particles may be characterized by their Stokes diameter. It was demonstrated through appropriate experiments that soot particles, which are approximately spherical in spite of being irregular in shape, may be classified in terms of the diameters of spheres having the same projection area \(x_p\) \[5\].

Because the scattering characteristics of particles depend on their material nature, the light scattering analyser had to be calibrated, i.e. it was necessary to determine experimentally the correlation between impulse height and particle size. For this purpose, the procedure described in detail by Liu et al. \[6\] was employed. This requires the determination of the impulse height distribution for a given substance (i.e. the soot agglomerates in this case) by means of the light scattering analyser as well as the corresponding particle size distribution. The determination of the size distribution was achieved by analyzing scanning electron micrographs taken of particles collected on a Nuclepore filter.

The relation between the signal height and the particle size arises from the correspondence of similar values in both cumulative distributions by number as illustrated in Fig. 5. Thus, the signal height \(U_1\) corresponds to the particle size \(x_{n1}\), etc. Fig. 6 shows the calibration curve for soot obtained in this way. Again, the particle

![Fig. 5. Impulse height distribution and corresponding particle size distribution.](image)

![Fig. 6. Calibration curve for soot particles.](image)
characteristic on the basis of the diameter of a sphere which has the same projection area $x_p$ was established on the grounds of the calibration methodology. A comparison with the calibration curve for latex particles illustrates the expected correlation, i.e. the fact that soot particles, due to their absorbing properties, scatter less light than latex particles of the same size. Since the procedure employed permits no statement concerning the extension of the calibration curve below 0.8 µm or above 7 µm, an extrapolation of the curve was necessary over these ranges. For particle sizes above 7 µm, we are in an area of application of geometrical optics which is characterized by a geometrical relation between impulse height and particle size. This is confirmed by the calibration curve for latex and applies equally to soot particles. The downward extension of the curve was effectuated by analogy with the progression of the curve obtained for latex. As particles below 0.7 µm are detected by the DMPS system, any inaccuracies in the extrapolation are limited to the size interval between 0.7 and 0.8 µm and hence are of little importance for practical purposes.

From the calibration as described above, the requirement for a combination of the distributions measured with the DMPS system and the light scattering analyser has been met. For this purpose, the particle flow density as measured by the light scattering analyser is converted to particle concentrations for each different range of particle size. The mathematical correlation of the size distribution thus prepared, with the results of the DMPS system which are given as particle concentrations for each different range of particle size, is achieved, initially, by calculating the number density distribution using the following equation:

$$q_N(x_p) = \frac{c_N(x_p)}{c_N \cdot \Delta x_p}$$

(1)

Here, $c_N$ is the sum of the particle concentration measurements obtained from both devices. By means of familiar equations, the cumulative distribution by number as well as distributions relating to volume may be calculated throughout from the number density distribution.

By way of an example for one particular operating state, the number density distribution obtained from the two individual distributions, with and without the application of a high voltage in the agglomerator is illustrated in Fig. 7. The good correspondence between the values at the point at which the two individual distributions connect is clearly visible, which means that both measuring methods yield the same particle concentrations over this size range. This result was not unexpected provided that the light scattering analyser was correctly calibrated. Another criterion that can be used to verify the efficiency of the combined measuring systems is the principle of mass conservation. Gravi-
combined measuring system, with and without agglomerator, for various operating states of the engine, taking into account the above assumptions. Again, a good correspondence between the values with and without agglomerator is observed. This means that the particles passing from the measuring range of the DMPS system into the range of the light scattering analyser are correctly detected by the latter. It follows that the combination of the DMPS system and the light scattering analyser allows the measurement of the size distribution of soot particles and agglomerates in the range between 17 nm and 40 μm. As to how the particle mass is bound in the agglomerates, it appears that the assumption that, in a macroscopic sense, the soot particles are spherical is reasonable.

3. Results and discussion

For investigations concerning the agglomeration phase, a range of motor operating levels were selected involving engine speeds from \( n = 1250 \text{ min}^{-1} \) to \( n = 3000 \text{ min}^{-1} \). The operating level is fully described by load \( L \) which is defined as the ratio of the actual and maximum brake mean effective pressure.

\[
L = \frac{p_{\text{me}}}{p_{\text{me, max}}}
\]

The influence of the motor operating level upon the efficiency of the agglomerator is illustrated by the results depicted in Figs. 9–11 in which the cumulative distribution by volume, with and without the agglomerator, is illustrated for three different operating points. For \( n = 1250 \text{ min}^{-1} \) and \( L = 25\% \) (Fig. 9), the particle mass moves almost completely into the range above 1 μm under the effect of high voltage. Approximately 60% of the mass was bound in agglomerates larger than 10 μm. What is striking is the abrupt increase in size distribution at approximately 5 μm, indicating that the 'production' of particles was not observed below this size. A similar size distribution was established in the upper size range at the operating point \( n = 2000 \text{ min}^{-1} \), \( L = 100\% \) (Fig. 10). Here again the size of the agglomerates exceeded 5 μm. In this case, however, not more than ca. 45% of the mass was bound in agglomerates. This suggests that a considerable portion of the unbound particles passed uninfluenced through the agglomerator. The flow rate in this latter operating state was 218 m³ h⁻¹ as against 63 m³ h⁻¹ in the first mentioned case, so that the residence time of the particles in the agglomerator was correspondingly shorter. The size distribution in Fig. 11 illustrates the situation for an operating state where \( n = 3000 \text{ min}^{-1} \) and \( L = 25\% \), and shows that even at such high volume flows considerable agglomeration was possible in principle. In this case, the proportion of agglomerates in the range above 1 μm was greater than 90%.

A precondition for the interpretation of these results is a detailed knowledge of the agglomeration mecha-
nism and the fundamental parameters which influence this mechanism. Unfortunately, only works dealing with the basics are to be found on this subject in the literature. Thus, according to the opinions of Polach and Hägele [2] the agglomerates stem from a redispersed wall deposit. On the basis of this mechanism, the process of agglomeration is divided into three phases: particle transport towards the collecting electrode; formation of the agglomerates at the electrode; and redispersion. However, general experience shows that this type of agglomeration only occurs in electrically conductive dusts since electrical conductivity has a significant influence on the behaviour of the particles at the collecting electrode.

Thus experiments conducted by Riehle et al. [7] with graphite demonstrated that the conductive particles accumulate in dendritic structures at the collecting electrode. This behaviour may be explained by recharging of the collected particles to the potential of the collecting electrode. This causes a focusing of the lines of the electric field so that the collected particles act as a nucleus at which other particles accumulate. Hence, through the influence of the discharge electrode, image forces are induced in the collected structures which are directed away from the collecting electrode and which, in the case of graphite, are sufficient to overcome the interparticle adhesive forces and cause a redispersion of the particles.

In the present work, the soot particles at the collecting electrode of the agglomerator show basically the same accumulation behaviour as graphite. Fig. 12 shows an example of a scanning electron micrograph of the situation with the soot particles for one particular operating level of the engine. Irregular coating of the electrode by the particle agglomerates is clearly visible.

For both fluid forces as well as electrostatic forces, these accumulations represent exposed points which are more likely to be redispersed. By virtue of their shape and size, these structures may be identified as the precursors of agglomerates. It follows therefore, that as a precondition for a soot particle to be bound to an agglomerate it must reach the collecting electrode of the agglomerator.

The proportion of particles which can theoretically be collected is determined by the ratio of the electric velocity of migration and the axial flow velocity in the agglomerator. These parameters can be varied in different ways. The electric velocity of migration may be directly influenced, for instance, by varying the agglomerator voltage. As the voltage is increased, the velocity of migration is increased and hence the proportion of particles agglomerated also increases [5]. The same effect is produced by reducing the exhaust gas flow at constant operating engine conditions, which may be achieved by inserting a bypass upstream to the agglomerator. Fig. 13 illustrates the effect to be expected for an operating level \( n = 3000 \text{ min}^{-1} \) at \( L = 25\% \). On decreasing the flow rate, i.e. increasing the residence time, the proportion of particles bound in agglomerates increases. In addition, an increase in the maximum size of the agglomerate can be observed with decreasing flow rate.

Apart from the electrostatic forces already mentioned, fluid forces also apparently play an important role with respect to redispersion. At low velocities, the structures formed can reach quite large dimensions before being emitted from the agglomerator. Such studies of the influence of residence time have also been carried out for different engine operating levels. In this connection, it was notable that even when the engine was operating at maximum load there was no significant effect on the residence time. This indicates that in this case particle transport, i.e. the portion of particles reaching the collecting electrode, is not the factor governing the observed low efficiency of the agglomerator.
ing volume flows lead to disagglomeration effects which ceramic filters. There are two approaches for a possible improvement of the method. The collection of agglomerates at high load operating states of the engine. This behaviour cannot be attributed to residence time problems as is clear from the investigations described. The reason must therefore be sought in the accumulation and redispersion of the agglomerates at the wall, and not in the transport of the particles to the collection electrode. Further research is necessary to elucidate to what extent the aerosol properties, which are influenced significantly by the operating state of the engine, are of importance in this respect. This means that an explanation for such behaviour must be sought in the other phases of the agglomeration process, i.e. accumulation and re-entrainment at the collecting electrode. Of particular interest in this connection is the importance of aerosol properties which are influenced significantly by the operating level of the engine. Investigations conducted using a laboratory appliance have indicated that the structure of the separated soot layer is very sensitive to the surface characteristics of the particles [5]. With the present state of knowledge, it is not possible to draw any conclusions on the relation between these phenomena and the size distribution of the agglomerates.

Table 1 lists the gravimetrically determined total collection efficiencies achieved with the two-stage system. The values vary between 43% and 87% depending on the various operating states and thus are in the range of collection efficiencies which can be achieved by ceramic filters. The distinct dependence on the load and engine speed is mainly caused by two effects. As mentioned above, the proportion of agglomerates bound in particles decreases with increasing engine load, leading to a finer feed distribution for the cyclone and resulting in a decrease of total collection efficiency at high loads. The increasing breakdown of the agglomerates at high velocities in the turbulent vortex flow of the cyclone is the factor responsible for the decrease in collection efficiency at increasing engine speed [8].

Table 1

<table>
<thead>
<tr>
<th>n (min⁻¹)</th>
<th>L (%)</th>
<th>E₃ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250</td>
<td>25</td>
<td>87</td>
</tr>
<tr>
<td>2000</td>
<td>50</td>
<td>68</td>
</tr>
<tr>
<td>2500</td>
<td>100</td>
<td>52</td>
</tr>
<tr>
<td>3000</td>
<td>25</td>
<td>43</td>
</tr>
</tbody>
</table>

a $Uᵦ = -10$ kV, $V₂ = 3 m₃ h⁻¹$.

4. Conclusions

As the results described above show, the two-stage collection system provides a feasible alternative to the ceramic filters. There are two approaches for a possible improvement of the method. The collection of agglomerates may be easily improved. One way is to modify the cyclone geometry so as to cause a reduction in the velocity. Although quite unusual for a cyclone, this procedure seems promising in this case because increasing volume flows lead to disagglomeration effects which have a negative impact on the total collection efficiency. No feasible approach exists to date for improving the low efficiency of the agglomerator at high load operating states of the engine. This behaviour cannot be attributed to residence time problems as is clear from the investigations described. The reason must therefore be sought in the accumulation and redispersion of the agglomerates at the wall, and not in the transport of the particles to the collection electrode. Further research is necessary to elucidate to what extent the aerosol properties, which are influenced significantly by the operating state of the engine, are of importance in this respect.

Nomenclature

- $cₙ$: number concentration, cm⁻³
- $cᵥ$: volume concentration
- $E₃$: total collection efficiency
- $n$: engine speed, min⁻¹
- $L$: engine loading, %
- $Pₑmc$: break mean effective pressure, bar
- $Pₑmc,max$: maximum brake mean effective pressure, bar
- $q₀(xₚ)$: number density distribution, μm⁻¹
- $Q₀(xₚ)$: cumulative distribution by number
- $Q₃(xₚ)$: cumulative distribution by volume
- $U$: impulse height, mV
- $Uᵦ$: agglomerator voltage, kV
- $Vᵦ$: exhaust flow rate, m³ h⁻¹
- $V₂$: extracted flow rate at the dust outlet of the cyclone, m₃ h⁻¹
- $xₚ$: equivalent diameter, μm

References
