Critical review of vacuum cleaner test methodology

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Introduction

Presently, almost everyone is satisfied with his/her vacuum cleaner and aware of the fact that advanced filter systems reduce the emission of dust in the exhaust air. Small particles penetrating the paper dust bag, and particles emitted from the coal brushes of the electromotor are filtered by a motor protection filter and finally by exhaust (post) filters. These filters vary in design and quality, from coarse filters to HEPA or S-class filters. For this reason performance testing of vacuum cleaners becomes more and more important, to aid in assessing the quality of the various brands. The exhaust emission should be measured accurately and reproducible.

The current DIN 44956/2 test method (Performance of vacuum cleaners) originated in the 1980s, and was partly derived from IEC 312. It prescribes the duct in which the vacuum cleaner is placed, the dust-feeder which feeds the test dust to the vacuum cleaner, and the methodology for calculating the mass emission value in mg/m³. The basic idea is that the emitted particle concentration is measured with an optical particle counter, while a fixed concentration of 550 mg/m³ AC Fine dust is sucked into the vacuum cleaner during a 2 minutes period.

3M as leading company in manufacturing high quality motor protection and post filters, took the initiative to review the test methodology and improve there where applicable. This paper presents a detailed review of the existing standard and the additions made by 3M. The suggested improvements include changes in the actual set-up as well as changes in the test methodology.

Contents

Why have an emission test?

In brief, because dust released by vacuum cleaners can damage health. Ultra-fine (submicron) dust escaping from the vacuum cleaner bag and particles released by the motor's carbon brushes can cause allergies and other health problems. When inhaled, up to 25% of the particles between 0.1 and 0.5 µm remain in the bronchial tubes, which may, depending on the type of dust, be health damaging. Consequently, it has become necessary to reduce dust emission levels and the market has responded by producing various filter systems. These include mechanical filters, and also electret filters, which 3M has been supplying to a large number of vacuum cleaner manufacturers since 1983. Latest trends are the so-called S-class filter, which captures 99.97% of all particles over 0.3 µm and the activated carbon filter, which reduces unpleasant smells and noxious gases. Adequate testing equipment and methodology are essential for developments like these.

Test set-up and method

The current DIN 44956/2 test uses a set-up as shown in Figure 1. The test hood consists of a sheet metal box in which canister as well as upright vacuum cleaners can be placed. On top of the truncated pyramid a circular tube with 100 mm inner diameter functions as an exhaust chimney. From this chimney, a part of the airflow is fed to an optical particle counter. The counter's lower size limit is 0.3 µm and the upper size limit is 20 µm At the bottom of the test hood, there is a slot through which the suction hose and the main cord are led. At the inlet of the suction hose, a rotating disk dust disperser is placed, capable of feeding AC Fine dust at a constant rate for a period of two minutes. The applied dust mass corresponds to a mean dust concentration of 550 mg/m³ during the two minutes measuring time, with the vacuum cleaner running at its maximum speed. A single mass emission value is to be calculated, which is the sum of the mass emissions for all size classes. The individual mass emissions are calculated assuming that all particles counted in a size class can be characterised with an average mass density, and an average equivalent sphere diameter equalling the size class median value.

Test duct

The test duct should feed the test dust to the vacuum cleaner uniformly over the required time period, and feed the emitted dust efficiently to the detection system. Because of its position, with its detection point approximately 1.5 metres above the vacuum cleaners exhaust position, one might expect significant large particle losses due to gravity. However, reasoning from the real life situation, the vacuum cleaner is placed on the floor and the detection point, which is comparable to the position of the respiratory tract of the person vacuum-cleaning is some 1.5 meters above. The small particles will reach this height easily and are in effect more important, because they are proven to be health damaging. Particles which are unable to reach the detection point cannot be inhaled, and therefore not important from a health point of view.

Test dust, dust disperser and dust sampling

Unfortunately, household dust is ill defined. For this reason SAE dust (formerly known as Air Cleaner test dust) is used, but this used to be classified inaccurately. The established tolerance level of ±3% for only six particle size channels in the AC test dust is too large to guarantee reproducible test results. The recently re-specified SAE "fine" dust, with ten size classes with a lower limit of 1 µm and smaller tolerances, is much more suitable. Particles released from the motor's carbon brushes form another dust source, responsible for a continuous emission in the range from 0.001 to 0.01 mg/m^3. These particles are mostly submicron and, dependent on the level of filtration, can have a great influence on the emission value. Imagine a vacuum cleaner with an S-class filter placed in front of the motor and a low efficiency filter in the exhaust port. The emitted carbon brush particles will result in a low test rating for the vacuum cleaner, regardless of the high performance of the S-class filter. We therefore recommend measuring the emitted carbon brush particles separately. The final emission results can next be corrected for their optical properties, as described in the section "particle sizer calbration".

The dust disperser should disperse the complete particle size range of the test dust efficiently, and also maintain a constant dust concentration throughout the test period. The suggested turntable system does not meet these requirements. In practice, it is difficult to divide the test dust uniformly which leads to variations in particle size distribution. Furthermore, the dust on the turntable disk is sucked away by the suction force of the tested vacuum cleaner. Since the suction force varies from one vacuum cleaner to another, the particle size distribution will vary as well. A rotating brush disperser (e.g. the RBG 1000 from Palas, Karlsruhe Germany) is a better choice. The rotating brush and compressed air facility employed in this type of generator ensure that the particle size distribution of the resulting aerosol is independent of the suction force of the vacuum cleaner.

When the dust has been dispersed, the resulting aerosol has to be sampled in such a way that the concentration can be measured representatively. The following aspects are important in order to avoid size selective sampling:

- The sample should be extracted parallel to the main flow,
- The tubes leading to the detector should be short, with wide bends, and constructed out of a conducting material.
- The sample should be extracted isokinetically.

Although it is generally assumed that a slight deviation from the isokinetic condition is permitted, the influence on the measurement results can be significant, when the measured number concentrations are converted to mass emission values. By measuring the fractional particle concentration both upstream and downstream from the vacuum cleaner, the effects of anisokinetic sampling are eliminated, and systematic errors are prevented.

Particle sizer calibration, count efficiency losses and count accuracy

Optical particle sizers are generally calibrated with latex particles. These are spherical, and have a known density (1050 kg/m^3) and refractive index (n=1.59-0i). In practise sizing errors occur, since real life particles are often not spherical and their optical properties differ from those of the latex calibration particles. In vacuum cleaner testing we are mostly concerned with SAE dust and, to a lesser extent, with carbon brush particles. The consequences are visualised in Figure 2, constructed using a MIE program. It shows the calculated response curves for a PMS LAS-X particle sizer, for the three particle types. It is clear that both SAE and carbon particles are substantially undersized by an instrument calibrated with latex particles. This will lead to errors, when the measured number concentrations are converted to a mass emission value. One way to overcome this problem is to calibrate the detector with the test dust itself. An alternative is to correct the calculations for the shift in particle size.

Furthermore, it is a known fact that the lowest size channels of most optical particle sizers have a low count efficiency. Some particle sizers can even count as few as 30% of the real number of particles present in these channels. This has serious consequences for the calculated emission value, because the DIN procedure prescribes a lower particle size limit of 0.3 µm, which is exactly the detection limit of the preferred particle sizer. One way to overcome this problem is to use a particle sizer with a high count efficiency for the lowest size channels, or by selecting an instrument with a detection limit below 0.3 µm. The best solution though, is to measure the fractional particle concentration both upstream and downstream from the vacuum cleaner. This eliminates all count efficiency losses and with the emission calculation method described in this paper one can also calculate the conventional mass emission value.

An often underestimated problem is the count accuracy of optical particle counters. Many optical particle sizers do not classify the measured particles correctly, even when the calibration problems described above are left out of consideration. We demonstrated this in the following experiment. A monodisperse aerosol was produced by nebulising a suspension of Uniform Latex Microspheres (Duke Scientific, Palo Alto CA; product nr. 5100A, nominal diameter 1.07 µm, 1.3% CV), after which the size distribution was narrowed even further with a differential mobility analyser. The resulting aerosol was fed to two different particle sizers: a LAS-X (Particle Measuring Systems, Boulder CO) and a MicroAir™ 5250 (HIAC/ROYCO, Silver Spring MD). The resulting particle size distributions are very different, as can be seen from Figure 3. The LAS-X classifies the 1 µm particles in two size channels. This is not surprising, as the cut-off between these two channels lies exactly at 1.0 µm. Whether 1 µm particles are counted in one or the other channel is governed by electrical and physical phenomena. The MicroAir™ 5250 produces a completely different result: although a monodisperse aerosol of 1 µm diameter was generated, large numbers of particles are counted in virtually all size channels, ranging from 0.5 to 20 µm. If these data are used in the calculation of a mass emission value - whereby the particle diameter is cubed - the result will undoubtedly be erroneous.

Dilution system

Depending on the efficiency of the vacuum cleaner's filter system, the emitted dust concentration can be so high it is necessary to reduce the concentration by diluting the sample. Two commonly used systems are available:

- a system where part of the sample flow is sent through a capillary tube, and the remaining part is cleaned using HEPA filters, and
- a venturi system, where the concentration is reduced by adding (filtered) compressed air.

Both systems have distinct advantages and disadvantages, related to the size and time dependency of the dilution factor. As an example: due to their inertia 15 µm particles can penetrate the dilution system with an efficiency of only 30%. We therefore recommend to measure the dilution factor as a function of particle size, so that this can be taken into account in the emission calculations.

Emission calculations

According to the DIN 44956/2 procedure, a single mass emission value is to be calculated, which is the sum of the mass emissions for all size classes. The individual mass emissions are calculated assuming that all particles counted in a size class can be characterised with an average mass density, and an average equivalent sphere diameter equalling the size class median value. As both of these assumptions can lead to errors, we suggest an alternative way to present the results. In stead of reporting just one total mass emission value, it is also possible to give the fractional efficiency of the vacuum cleaner's filter system. This gives more detailed information, and it also eliminates potential systematic errors caused by differences between test dust batches. In addition, the mass emission can be calculated with greater accuracy, when the fractional efficiency is combined with the volume averaged particle size distribution for SAE dust, which is available from the supplier (Powder Technology Incorporated, Burnsville MN).

Results

In order to find out how mass emission values compare with consumer test ratings, we set up a small experiment. We selected two of the vacuum cleaners which were tested in 1993 by the *"Stiftung Waren Test"*. In the test, these vacuum cleaners were qualified as "satisfactory" and "very good" respectively. We performed standard tests according to the modified DIN test described above, and found mass emission values of 0.772 mg/m^3 and 0.052 mg/m^3. It is obvious that there is a good agreement between the rating according to the mass emission values and the rating in the consumer test. The question is though, what kind of rating a vacuum cleaner should get with a mass emission of 0.001 mg/m^3 (e.g. with an S-class filter) should get. In order to investigate the performance of the S-class filter, we equipped one of our vacuum cleaners with such a filter. The measured mass emission value (0.002 mg/m^3) is much lower than the value found with the original GS200 flat filter (0.018 mg/m^3).

However, not every vacuum cleaner reaches the same level of emission with an S-class filter. We tried to visualise this by another experiment, in which two completely different vacuum cleaners were equipped with S-class filters. For the one vacuum cleaner we found an emission value of 0.0001 mg/m^3, which is 20 times lower than the value found for the other one (0.002 mg/m^3). This clearly shows that an S-class filter, with an efficiency of 99.97% for particles of 0.3 µm, does not always give the same emission value. The emission value is specific for a certain vacuum cleaner, and therefore influenced by sealing problems and flow patterns.

The ideal test method should yield consistent results, regardless of the detection instrument. The mass emission for a given vacuum cleaner-filter combination should therefore always have the same value. To check this consistency, a vacuum cleaner was tested using two different detection instruments: a LAS-X (Particle Measuring Systems, Boulder CO) and a CI-226 (Climet Instruments, Redlands CA). The test was performed twice, once with a GS200 filter installed and once with a S-class filter installed, adding up to a total of four tests. The mass emission for every experiment was calculated according to the conventional DIN method, and according to the improved 3M method. The results are shown in Table 1.

Table 1. Mass emission values (in mg/m^3) for two different filters, measured with two different instruments. The relevant ratio's are also tabulated.

	LAS-X		CI-226		ratio	
	DIN	3M	DIN	3M	DIN	3M
GS200 filter	0.0180	0.0160	0.0240	0.0100	**0.75**	**1.60**
S-class filter	0.0019	0.0013	0.0017	0.0008	**1.12**	**1.63**
ratio	**9.47**	**12.3**	**14.1**	**12.5**		

The results show that testing a filter with two different instruments yields different mass emission values, both with the DIN and with the 3M method. This is not surprising, because neither instrument is calibrated with SAE and they have different measuring optics and wavelengths. Nevertheless, the influence of the detection instrument is much stronger and less predictable for the DIN method. Additionally, particle losses and errors caused by count efficiency losses will have a negative effect. Where the 3M method yields results which consistently reflect the difference in performance between the two selected filters types, the DIN method fails. This is illustrated quantitatively by the ratio's listed in the table: the difference in ratio is negligible for the 3M method (2%), but substantial for the DIN method (49%).

Conclusions

It can be concluded from the preceding, that the accuracy of the test results is increased substantially. Systematic errors caused by varying vacuum cleaner capacities, sampling and counting losses, and detector characteristics are avoided by a number of improvements. These improvements include changes in the actual set-up, shown in Figure 4 (using a different dust disperser, using a venturi-type diluter and sampling isokinetically), as well as changes in the method (correcting for the emission of carbon brush particles, taking the optical properties of the test dust into account and sampling upstream and downstream from the vacuum cleaner). The experimental observations in the previous section clearly show that the method for calculating mass emissions proposed in this paper is more reliable. The result is more consistent and less dependent on the equipment used. Furthermore we suggest measuring a fractional efficiency for a filter system, in addition to the mass emission value. Since detailed data is available, sudden changes in emission can be registered, as well as specific filtration characteristics.

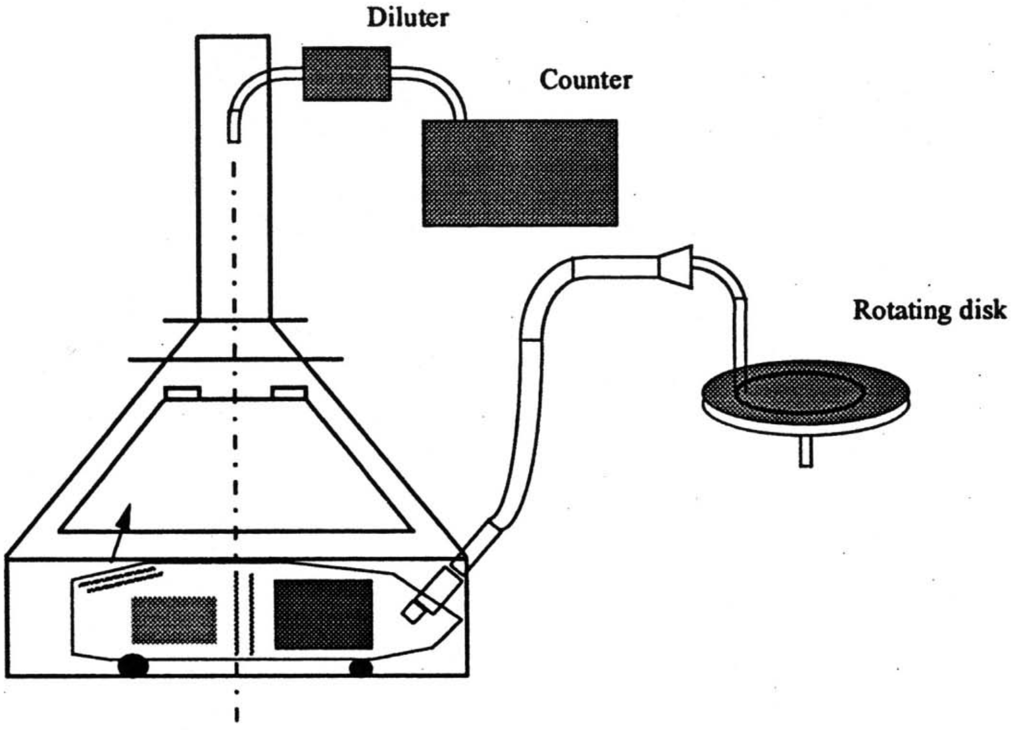

Figure 1. Schematic overview of the test set-up described in DIN standard 44956/2.

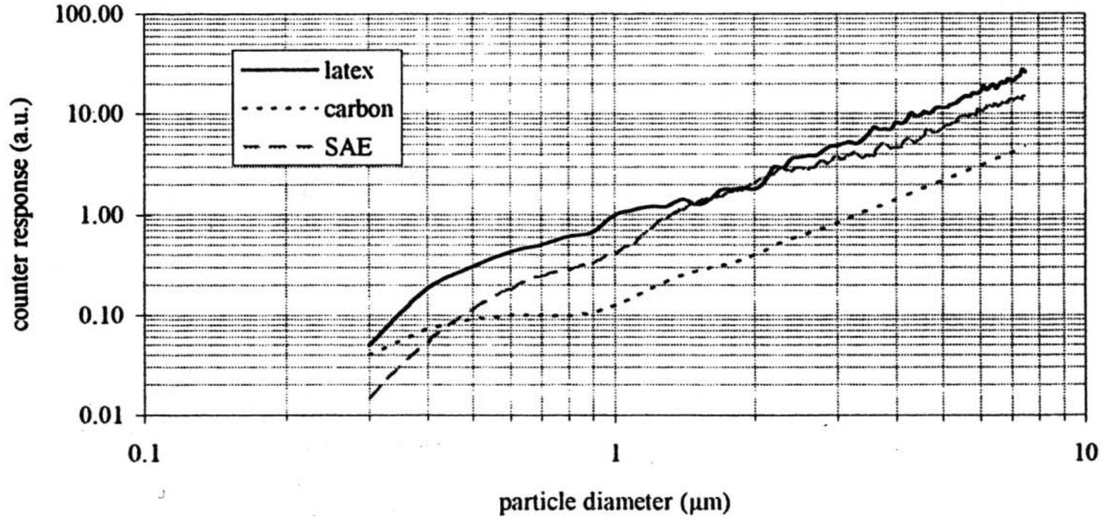

Figure 2. Response curves for a LAS-X particle sizer, constructed using a MIE program

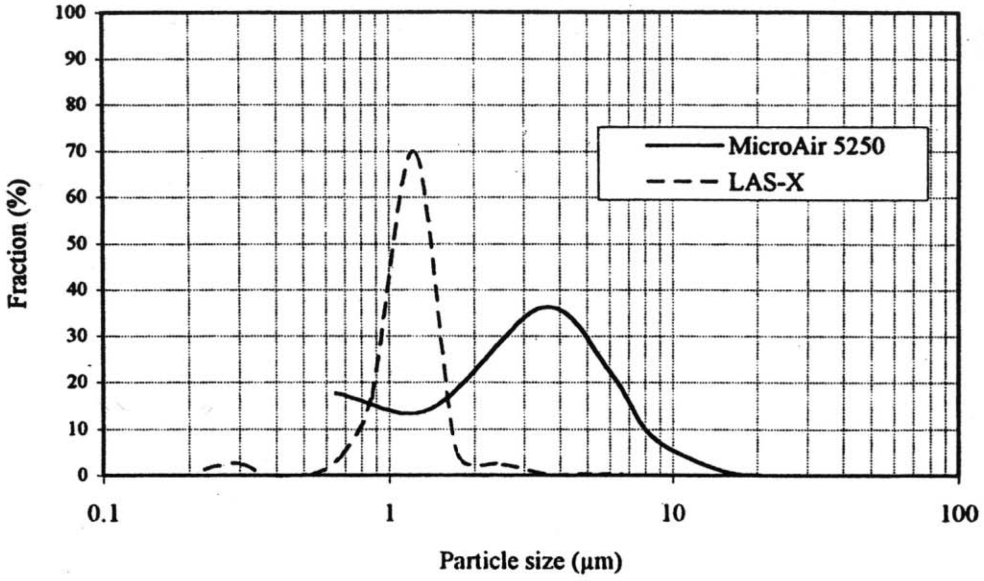

Figure 3. Particle size distribution of a monodisperse latex aerosol (1.07 µm), measured with a LAS-X and a MicroAir™ 5250 optical particle sizer.

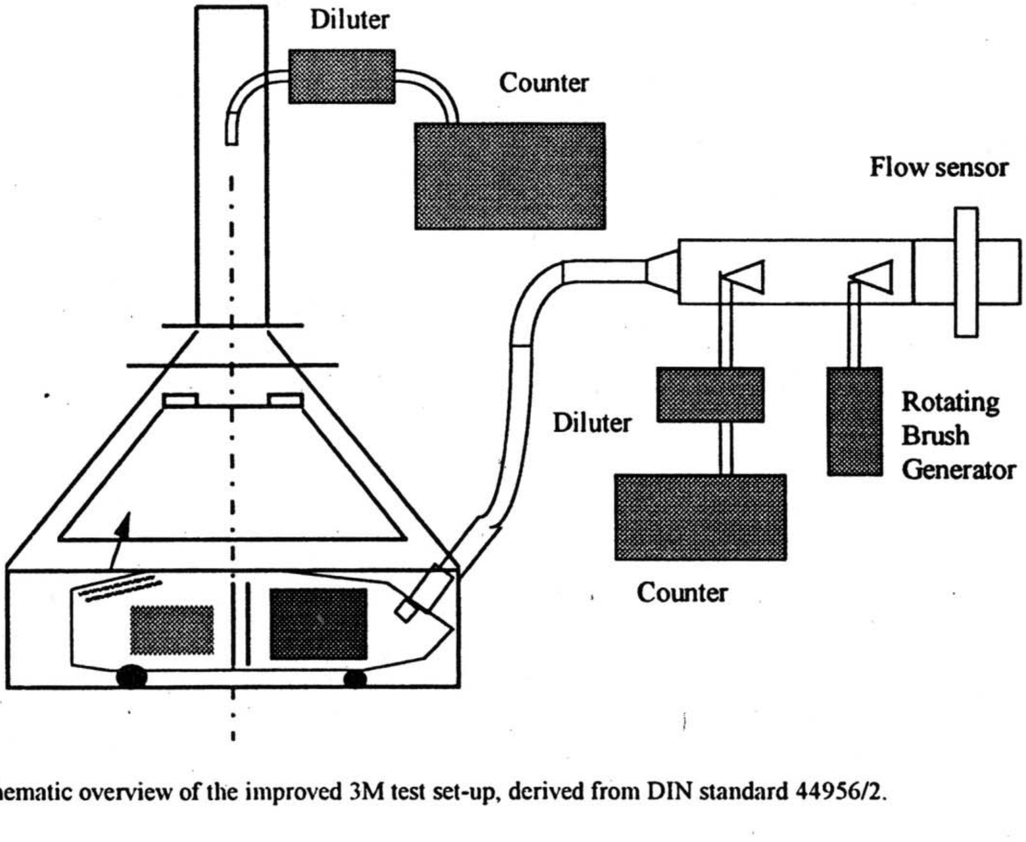

Figure 4. Schematic overview of the improved 3M test set-up, derived from DIN standard 44956/2.