Methods for Measuring Performance of Vehicle Cab Air Cleaning Systems Against Aerosols and Vapours

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Vehicle cabs equipped with an effective air cleaning and pressurization system, fitted to agricultural and off-road machineries, isolate drivers from the polluted environment, in which they are likely to work. These cabs provide protection against particulate and gaseous pollutants generated by these types of work activities. Two laboratory methods have been applied to determining the performance characteristics of two cabs of different design, namely, optical counting-based measurement of a potassium chloride (KCl) aerosol and fluorescein aerosol-based tracing. Results of cab confinement efficiency measurements agreed closely for these two methods implemented in the study. Measurements showed that high confinement efficiencies can be achieved with cabs, which are properly designed in ventilation/cleaning/airtightness terms. We also noted the importance of filter mounting airtightness, in which the smallest defect is reflected by significant degradation in cab performance. Determination of clean airflow rate by monitoring the decrease in test aerosol concentration in the test chamber gave excellent results. This method could represent an attractive alternative to methods involving gas tracing or air velocity measurement at blowing inlets.

Keywords: aerosol; cab; optical counter; tracing

INTRODUCTION

In a pressurized vehicle cab, where the air supplied is appropriately purified, driver exposure to pollutants can be reduced by at least a factor 10 (Hall et al., 2002) and isolate the driver from the polluted environment, in which he is likely to work. These cabs are found in a number of sectors: civil engineering construction (demolition, decontamination of polluted soils, tunnel excavation, and road surfacing), handling (powder products and waste sorting), mining industry, and in the agricultural sector (pesticide spraying). These cab cleaning systems reduce driver exposure to aerosols (dust, fibres, diesel particles, bioaerosols, etc.) and vapours [NH₃, volatile organic compounds (VOC), etc.]. A blower motor pressurizes the cab with cleaned air and recirculates a part of this airflow rate through the air conditioning (heating) system. Generally, the air cleaning system comprises a particle pre-filter followed by a high-efficiency terminal filter and for certain operations by an adsorption stage made of activated carbon for vapour separation. Some ventilation systems enable recirculation of a part of the air of the cab to filters after its reintroduction. This interesting solution, which allows control of the resuspended particles from the internal surfaces of the cab, is unfortunately not much implemented.

To ensure effective protection, the cab must fulfil the following functions:

– Air supplied to the cab must be cleaned with respect to all pollutants it is likely to contain. To achieve this, the cleaning system must be designed to stop dust particles, aerosols, gases, and vapours. Particle penetration (ratio of concentration inside the cab to outside) shall be <0.5% for particles diameter between 1 and 5 μm according to draft European Standard prEN 15695 (2008) designed for agricultural machine cabs. Other specifications can be found in American Society of Agricultural Engineers (ASAE) Standard S525–1 (1997).

– The cab must be capable of being maintained at a slight (20–50 Pa) overpressure to curtail entry of contaminated air through leakage areas (location of the different controls, doors and windshield seals, etc.) under air pressure created by machine movement and external conditions (see Appendix A1).

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– The cab must remain totally closed during the entire operation. Internal temperature rise, especially due to radiation, must therefore be counteracted by an efficient air cooling system.
– In the event of accidental cab contamination (e.g. during door opening), the cleaned airflow must be high enough to limit driver exposure with respect to time.
– A cab operating fault detection system must be integrated: pressure measurement (currently offered by some manufacturers) and detection of pollutants in the driver compartment (sometimes provided for VOC).

At least three criteria must be met for a cab to fulfil properly its function: pressurization, minimum penetration with respect to the main pollutants, and cleaned airflow rate.

A number of research studies have been conducted to develop and test methods for establishing cab performance in laboratory or in the field (Heitbrink et al., 2003; Thorpe et al., 2003; Organiscak and Cecala, 2008). In this study, various methods have been applied for determining in the laboratory the performance characteristics of two cabs of different design.

**METHODS**

Cab 1, used for agricultural operations, was originally designed to be pressurized and supplied with filtered air. This cab’s cleaning system comprises a pre-filter followed by a high-efficiency (99.995%, NaCl test) filter. Tests were conducted at fan speed 1 (three speeds), which generated a cab overpressure of 20 Pa.

Cab 2, representing the second system tested, is intended for fitting to a civil engineering construction machine and was not initially designed to be pressurized. Extra cab sealing work is therefore sometimes needed to ensure its pressurization.

It comprises a fan, a particle pre-filter, a terminal filter [FFP3 as per European Standard EN 149 (2001)—1% maximum penetration at 0.6 μm], followed by a stage incorporating 10 kg of activated carbon (Type A) for adsorbing vapours. This cleaning system is designed to be connected to the existing cab ventilation system. Under these conditions, the resulting cab overpressure is 125 Pa.

There is no recirculation of air through filters in these two cabins. Tests involved determining the cab confinement efficiency using different methods along with the cleaned airflow and pressurization. Measurements were only based on aerosols for Cab 1, which was only fitted with particle filters. Confinement with respect to a test gas was also studied for Cab 2, whose cleaning system integrated an adsorption stage.

**Confinement efficiency for an aerosol**

Confinement efficiency \((E)\) is defined based on the ratio of gas or aerosol concentration under steady-state conditions inside the cab \((C_i)\) to its concentration outside the cab \((C_e)\):

\[
E = 1 - \frac{C_i}{C_e}
\]

The cab is placed in a 288.6-m\(^3\) enclosed testing chamber, in which the aerosol or gas is generated. A fan rapidly ensures concentration homogeneity within the chamber (fan blade diameter 0.4 m, fan rotation speed 1420 tr min\(^{-1}\)). Internal and external concentrations are measured at a time \(t = 3\tau_{e}\), after aerosol/gas generation is stopped, to ensure steady-state conditions. The cab time constant \(\tau_{e} = \frac{V_c}{Q_e}\), in which \(V_c\) is the cab volume accessible to air and \(Q_e\) is the cleaned airflow rate.

**Efficiency measured by optical counting.** A KCl aerosol was generated by pneumatic atomization of a 1% (by mass) solution using a Root Lowel BP 1035 spraying system. Aerosol generation was stopped when the particle concentration reached the optical particle counter (OPC) saturation limit. The aerosol concentration shall never exceed the saturation limit of the OPC given by the manufacturer. A Grimm 1.108 optical counter (15 channels from 0.3 to 20 μm) was used to measure KCl aerosol concentrations. Samples were taken using 1.2 m-long carbon (TSI) antistatic tubes (ID = 8 mm). Five internal \((C_i)\) and external \((C_e)\) concentration sampling sequences were performed and controlled by two solenoid valves. \(C_i\) and \(C_e\) were established for each counter class by taking average values for the five sampling sequences. The confinement efficiency was then determined based on the ‘optical equivalent’ diameter of the particles. This method forms the basis of draft standard prEN 15695 (2008).

The main drawback of this method is the internal particle sources, which result in the efficiency being underestimated. Internal particle sources are essentially 2-fold: particles deposited on the cab internal walls returned to suspension by the ventilation system and carbon particles generated by certain types of blower motors. A correction procedure (Bémer et al., 2005) allows the influence of these internal particle sources to be attenuated. This involves performing five \(C_i\) and \(C_e\) concentration sampling sequences for two initial concentration \(C_e(0)\) values: a test with a high concentration \(C_e(0)\) near to the counter saturation concentration, followed by a test with a much lower concentration (saturation divided by ~10). This two-step correction procedure was applied in this study for the optical counting measurements.
Efficiency measured by fluorimetry. An ultrasonic nebulizer (Areco AR4-VE), also supplied with a 1% (by mass) solution, was used to generate the fluorescein aerosol. The concentration was measured either by filter sampling or by cascade impactors.

The fluorescein aerosol was sampled inside and outside the cab using two annular slot sampling probes (Roger et al., 1999), on quartz fibre filters (Whatman QMA, ø37 mm). The sampling flow rate of each system was kept constant by a sonic nozzle connected to a vacuum pump (KNF AN35). Internal and external sampling rates were 32.88 and 16.76 l min\(^{-1}\), respectively, and the sampling time was 20 min. Fluorimetry was applied to determine the mass of fluorescein collected by the filters and these were therefore placed in 50 ml of sodium tetraborate (Borax, pH 9) solution, whose fluorescence was measured at 485 nm (excitation) and 515 nm (emission) wavelengths (Jenway 6280 fluorimeter). Concentrations measured in this way led to determination of the ‘total’ confinement efficiency because the latter is defined for the entire aerosol and not for a given particle size class, as in the case of the optical counter.

The fluorescein aerosol particle size distribution inside and outside the cab was also measured using two impactors (Andersen Marple 298) with eight stages ranging from 0.5 to 20 µm (plus the final filter). Pumps (Gillian HFS-513A) were used for sampling at a rate of 3 l min\(^{-1}\). Cut-size diameters of the impactor were corrected to take into account the fact that the airflow rate was different from the nominal airflow (2 l min\(^{-1}\)) (Marple et al., 1993). The fluorescein particle quantities deposited on the nine impactor stages were also determined by fluorimetry, by placing the collection membranes in 10 ml of Borax solution at pH 9. The impactors measured the confinement efficiency with respect to the particle aerodynamic diameter.

A quartz impactor (QCMPC-2) was also used to monitor the aerosol particle size distribution outside the cab. This instrument allows instantaneous determination of the aerosol particle size distribution within a 0.07–15.7 µm size range. Figure 1 shows a photograph of the instrumented cab in the test chamber.

Confinement efficiency for a gas

A bubbler supplied with air at 60°C was used to produce a given quantity of cyclohexane vapour inside the test chamber containing the cab. When the cyclohexane concentration in the chamber reached ~100 p.p.m., gas production was stopped prior to starting sampling of cab external (C\(_{e}\)) and internal (C\(_{i}\)) concentrations using two polyamide tubes connected to two solenoid valves, which adjusted the sampling times. The cyclohexane concentration was determined by an infrared (IR) analyser (Miran sapphire). The capacity of the IR analyser internal pump was insufficient to ensure sampling, which was therefore performed by an auxiliary pump (KNF AN35) discharging the sampled air into a small glass tank, in which the air was finally sampled upstream of the analyser. Gas concentrations were processed on a computer via a data acquisition unit (Ahlborn, Almemo 2290-8).

Fig. 1. Photograph of test cab showing instrumentation. 1, optical counter; 2, sampling system; 3, external filter sampling; 4, external impactor; 5, internal filter sampling; 6, QCM impactor; 7, cab ventilation air intake; 8, ultrasonic aerosol generator; 9, aerosol nebulizer; and 10, mixing fan.
Measurement of cleaned airflow rate

Two methods were applied to determine the cleaned airflow rate, passing through the cleaning devices, i.e. particle filters and adsorbent: a conventional method using a tracer gas and an indirect method based on monitoring the decrease in KCl aerosol concentration in the test chamber by optical counting.

Tracer gas-based measurement. This method involved injecting, at the cab air inlet, a tracer gas (helium) at a known constant mass flow rate and measuring the tracer gas concentration inside the cab under steady-state conditions (NF X 10141, 1982). The helium concentration was determined using a mass spectrometer (Leybold, UL100+). The test chamber was left open to the exterior during measurement to prevent any recirculation of the tracer inside the cab.

Chamber aerosol concentration (Ce) monitoring-based measurement. This method involves generating a KCl aerosol in the test chamber and, after ceasing aerosol generation, monitoring the decrease in its concentration (Ce) by optical counting in two configurations: (i) cab ventilation stopped and (ii) cab ventilation operating. If concentration Ce is considered as homogeneous in the whole volume of the chamber, the filtered airflow rate Qc can then be determined from a mass balance equation giving (see Appendix A2)

$$Q_c = \frac{-(V_h - V_c)}{E}(p_+ - p_-),$$  (2)

in which $V_h$ is the test chamber volume and $V_c$ is the cab volume ($V_h = 288.6$ m$^3$; $V_c = 2$ m$^3$ for Cab 1 and 2.9 m$^3$ for Cab 2); $E$ is the confinement efficiency; $p_+$ is the slope (per second) of the straight line of the concentration decrease, expressed from the logarithm of Ce, with the cab ventilation operating; and $p_-$ is the gradient of the slope of ln(Ce) with the cab ventilation stopped. The same sampling device as described for the measurement of cab efficiency was used.

Test conditions for establishing slopes $p_+$ and $p_-$ must be absolutely identical (generated aerosol quantity, data recording, and chamber ventilation), except for the cab ventilation condition, obviously. Slopes $p_+$ and $p_-$ are determined from aerosol concentrations recorded between time $t_0 \approx 10$ min, which corresponds to the mixing time of the generated aerosol inside the test chamber and time $t_1 \approx 30$ min. $t_0$ is estimated at three times the chamber time constant $\tau_h = \frac{V_h}{Q_h}$, with $Q_h$ the flow rate generated by the mixing fan (4450 m$^3$ h$^{-1}$).

RESULTS

Confinement efficiency (aerosol)

Cab 1. Figure 2 illustrates the cab confinement efficiency measured by optical counting (KCl), corrected for internal particle sources, and by fluorescein tracing. The results have been plotted based on the particle equivalent volume diameter ($d_e$). However, impactor gives an aerodynamic diameter ($d_{ae}$) and an optical counter gives an equivalent optical diameter (dopt). The relationship between diameters $d_{ae}$ and $d_e$ is expressed by equation (3) (Hind, 1999):

$$d_{ae} = \left(\frac{\rho_p}{\rho_0 X}\right)^{1/2} \left(\frac{C(d_e)}{C(d_{ae})}\right)^{1/2} d_e,$$  (3)

where $\rho_p$ is the particle density (kilograms per cubic meter); $\rho_0 = 10^3$ kg m$^{-3}$; $X$ is the particle dynamic shape factor; and $C(d_e)$ and $C(d_{ae})$ are the slip correction factors applied to diameters $d_e$ and $d_{ae}$, respectively.

For virtually spherical fluorescein particles, equation (3) is solved using $X = 1$ and $\rho_p = 1.35$ g cm$^{-3}$ (Stöber and Flaschbart, 1973). Slip factors are computed by iterations (five or six are enough).

The optical particle diameter is considered equivalent to diameter $d_e$ because of the small difference between the KCl refractive index ($n = 1.49$) and that of the ‘latex’ particles used for calibrating the optical counter ($n = 1.59$) and if we assume the KCl particles are almost spherical [KCl crystals forming globular agglomerates (Ho and Bell, 1981)].

The filter-based total confinement efficiency is shown in Fig. 2 with respect to the particle mass mean diameter (MMD). This diameter was determined from mass mean aerodynamic diameters (MMADs) established using Marple and QCM impactors, located in the test chamber and by applying equation (3) in its reverse form. The latter two instruments gave very similar results, leading to a MMAD = 2.0 µm and thus a MMD = 1.74 µm.

These results show the good agreement between the different methods. They also show the significant difference between filter efficiency (99.995% at...
0.6 μm) and cab efficiency (≈99.2% at 0.6 μm). This difference would be the consequence of air infiltration through cab leaks.

Confinement efficiency (gas and aerosol)

**Cab 2.** Figure 3 presents five typical measuring sequences of cyclohexane concentrations $C_e$ and $C_i$. After testing, the concentration in the duct downstream the cleaning system ($C_c$) was measured and the analyser zero was checked. The internal concentration $C_i$, of the order of 12 p.p.m., equals the concentration measured in the duct ($C_c$). This relatively high $C_i$ value does not therefore result from infiltrations into the cab and this is indeed logical, given the high overpressure of 125 Pa inside the cab. The confinement efficiency for the test gas, derived from the internal and external mean concentrations, is 87.2%, i.e. a penetration of 12.8%. This high penetration could be caused by leaks inside the filter housing and not by a defect in the activated carbon bed, as test-bench investigations on this bed had shown. The concentration measured downstream of the activated carbon bed under a cyclohexane concentration of 119 p.p.m. is effectively zero. This indicates that there are no preferential paths within the activated carbon medium.

On the other hand, confinement for the aerosol (KCl and fluorescein) is much higher than confinement for the gas and it complies with the declared performance characteristics for the filters installed, i.e. 99% filter efficiency at 0.6 μm (Fig. 4). This graph shows the efficiency obtained in experimental acquisition of the five $C_e$ and $C_i$ sampling sequences and the efficiency determined in two experiments to correct the internal particle source effect. The efficiency measured from filter samples of the fluorescein aerosol agrees closely with the optical counting-based data. The MMD of the fluorescein aerosol was equal to 1 μm in that case.

**Cleaned airflow rate**

Measurements were only performed on Cab 1. The gas tracing-based cleaned airflow rate for Cab 1 is $118 \pm 3$ m$^3$ h$^{-1}$. Figure 5 shows the curves for KCl aerosol concentration decrease in the test chamber ($C_e$), measured by optical counting in the two configurations (with and without cab ventilation), as described earlier for the determination of slopes $p_+$ and $p_-.$

The concentration decrease was monitored from Grimm counter Classes 1 to 4, which correspond to particle sizes between 0.3 and 0.8 μm, so as to work with enough particles and eliminate the concentration decrease phenomenon resulting from sedimentation, which is insignificant in the submicronic size range. Efficiency $E$ in equation (2) therefore corresponds to the cab efficiency for the 0.3–0.8 μm particle size range, i.e. $E = 0.991$. Measured slopes $p_+$ and $p_-$ [equation (2)] are $p_- = -3485 \times 10^{-4}$ s$^{-1}$ and $p_+ = -4598 \times 10^{-4}$ s$^{-1}$, respectively. From this, we derive the filtered

![Fig. 3. Cyclohexane internal ($C_i$) and external ($C_e$) concentrations measured for Cab 2. Concentration measured in the air duct downstream the cleaning system at end of final cycle ($C_c$). Zero analyser at end of test.](https://academic.oup.com/annweh/article-abstract/53/4/441/295423)

![Fig. 4. Optical counting-based confinement efficiency of Cab 2 with respect to particle diameter: raw data, dashed lines; efficiency corrected for internal sources, straight line. Filter sampling and fluorimetry-based measurement, filled diamonds.](https://academic.oup.com/annweh/article-abstract/53/4/441/295423)

![Fig. 5. Concentration decrease for 0.3- to 0.8-μm particles in test chamber, with and without cab ventilation. Determination of slopes $p_+$ (dashed line) and $p_-$ (straight line), equation (2).](https://academic.oup.com/annweh/article-abstract/53/4/441/295423)
airflow rate $Q_c = 116.7 \pm 8.6 \text{ m}^3 \text{ h}^{-1}$. This experiment was repeated under identical conditions and gave a filtered airflow rate $Q_c = 119.1 \pm 8.8 \text{ m}^3 \text{ h}^{-1}$. The cause of the variability in the determination of $Q_c$ is essentially due to the incertitude on the measurement of slopes $p_+$ and $p_-$.

As we can see, airflow rates determined by the two methods, i.e. tracer gas and aerosol decrease, are very similar.

**CONCLUSION**

Cab confinement efficiency results based on different measurement methods agree closely. Adoption of a two-stage procedure allows us to correct the optical counting-based internal concentration $C_i$ for internal particle sources, but significantly complicates the method. On the other hand, a drawback of the fluorescein aerosol tracing method would be laboratory reticence towards contaminating test facilities with fluorescein particles, which are likely to be deposited on all wall surfaces and can only be removed by repeated washing with water.

These measurements also reveal that high confinement efficiencies can be achieved ($E > 99.5\%$, particle diameter $>1 \mu\text{m}$) for cabs correctly designed on a ventilation/cleaning/leaktightness basis. The cyclohexane gas tests showed that filter assembly leaktightness is of prime importance and that the slightest defect in this respect is reflected by a significant degradation in performance characteristics.

Clean airflow rate measurement based on monitoring the decrease in test aerosol concentration in the test chamber gave very satisfactory results. But, these should be complemented by other tests on differently designed cabs to validate fully this approach. The method could represent an interesting alternative to gas tracing or blowing inlet air velocity measurement methods due to its simplicity and, above all, to its requirement for the same instrumentation as that recommended for determining confinement efficiency.

Reliable methods are now available for determining the performance characteristics of a cleaned air cab in the laboratory.

Because the vehicles equipped with these cabs can be used in severe environments sometimes for many years, performances of such systems may deteriorate with time.

Efforts should now been pursued in two areas:

- the problem of filter life and thus of filter replacement frequency,
- \textit{in situ} evaluation of cab performance: installation of concentration sensors, monitoring of filter pressure drop, measurement of confinement efficiency, etc.

**APPENDIX A1: CAB OVERPRESSURE**

The dynamic pressure (pascal) exerted on a surface by the air movements can be estimated from the following relation:

$$P_d = \frac{\alpha}{2} \rho V^2,$$

where $\rho$ is the air density (kilograms per cubic meter), $V$ is the air velocity (meters per second) coming on the surface, and $\alpha$ is the pressure drop coefficient (0.85).

Thus, at normal thermodynamic conditions, an air velocity $>6.3 \text{ m s}^{-1}$ ($22.5 \text{ km h}^{-1}$) is necessary to overcome a static pressure of 20 Pa.

**APPENDIX A2: DETERMINATION OF THE FILTERED AIRFLOW RATE**

The airflow rate through the filter’s cab ($Q_c$) can be determined from two measurements of the decrease in aerosol concentration $C_c$ in the test chamber: when cab ventilation is operating and when cab ventilation is stopped. The mass balance equation describing this concentration decrease in the test chamber when cab ventilation if operating and assuming a complete mixing of the aerosol is

$$dM = -\beta (V_h - V_c) C_c dt - E Q_c C_c dt,$$

where $M$ is the mass of aerosol inside the test chamber (kilograms), $\beta$ the aerosol deposition coefficient (per second), $E$ the filter efficiency, and $V_h$ and $V_c$ are the test chamber and cab volumes, respectively. From equation (A2), we deduce the concentration decreasing rate ($p_+$) when cab ventilation is on:

$$\frac{\text{dln}(C_c)}{\text{dr}} = -\beta - \frac{E Q_c}{(V_h - V_c)} = p_+.$$

When cab ventilation is stopped, the concentration decreasing rate is simply:

$$\frac{\text{dln}(C_c)}{\text{dr}} = -\beta = p_-. \quad (A4)$$

Subtracting equation (A3) from equation (A4) gives the airflow rate $Q_c$:

$$Q_c = - (p_+ - p_-) \frac{(V_h - V_c)}{E}. \quad (A5)$$

**REFERENCES**

Part 1: definitions, test method, and safety practices.


