Combining air filtration with ultra-fine particle sensing for an enhanced energy-efficient indoor air quality optimization

Johan Marra

Philips Research Laboratories
High Tech Campus 4; Postal Box WAG-01
5656 AE Eindhoven, The Netherlands

Corresponding E-mail: johan.marra@philips.com

SUMMARY

A satisfactory indoor air quality (IAQ) relies, amongst other things, on the availability of clean ventilation air. The outdoor air cleanliness in many urban environments is far from optimum. Fine particles (FPs ≤ 2.5 μm) and certainly ultra-fine particles (UFPs ≤ 0.3 μm) feature prominently as hazardous constituents of common urban air pollution. Installed filters in ventilation units of buildings and cars can clean mechanically supplied ventilation air. However, because affordable particle sensors of sufficient reliability and robustness are not commercially available, the degree to which the applied ventilation and filtration strategy is able to control the absolute indoor pollution level at any time remains usually unknown. This paper introduces a UFP sensor capable of recording the ambient UFP pollution level, yielding a sensor signal that relates to the relative inhalation-induced health hazard of airborne UFPs. The monitoring functionality of this sensor can be used for creating awareness with regard to the ambient UFP pollution level. For control purposes, UFP sensors can be used in addition to common T, RH and CO_2 sensors. Furthermore, a new type of electrostatically-enhanced particle filter is presented that accomplishes its air cleaning functionality in a more energy-efficient way than a comparable mechanical filter. Providing air handling units with particle filters as well as with UFP sensors downstream of these filters and/or in indoor spaces allows for a versatile control of air handling units that explicitly takes the indoor UFP pollution level into account as a decision factor for the ventilation strategy. This enables an enhanced sensor-controlled fine-tuning of the IAQ with anticipated savings in power consumption.

INTRODUCTION

In the Western World, most people spend over 90% of their time in indoor environments such as homes, offices and cars. The indoor air quality is therefore very relevant for human health and comfort. Important indoor air quality parameters comprise the temperature (T), the relative humidity (RH), the CO_2 level and the air pollution level [1]. In recent years human productivity has also been found to depend on the indoor air quality [2 - 3], thereby further emphasizing the economic significance of optimized air quality parameters. Several air treatment/handling devices (fans, heaters, coolers, (de) humidifiers, ventilation systems, cleaning systems) are often present to help maintaining an acceptable indoor air quality. However, the energy-hungriness of these devices and rising energy prices have since long promoted energy saving measures such as better home/building insulation and partial air re-circulation by air handling units. An accompanying aspect of the latter measures is a generally decreased ventilation rate. Ample evidence has come forth [4] that the decreased ventilation rates are frequently insufficient for maintaining an acceptable if not optimum indoor air quality, and are at least partly responsible for an overall increasing indoor air pollution level.

Indoor air pollution is directly related to various diseases, feelings of discomfort, reduced work performance and a diminished learning capability at school [4]. Part of the indoor pollution comes from indoor sources such as outgassing building materials and equipment, human bio-effluents, and activities like cooking and smoking. Supplied ventilation air and/or exhaust indeed diminish the pollutant concentration derived from indoor sources through dilution, however ventilation also introduces pollutants from outdoors. Hazardous outdoor pollutant species comprise allergenic particles (e.g. pollen), bioaerosols, and particles/gases originating from automobiles and industrial activities. Especially the fine particles (FP ≤ 2.5 μm) and even more so the ultra fine particles (UFPs ≤ 0.3 μm) derived from combustion processes (e.g. soot particles) are currently receiving much attention from various legislative authorities because of their demonstrated long-term impact on human health [5]. Outdoor particle concentrations vary considerably in time and place but are relatively highest in urban areas and/or close to motorways. As of today, the use of air filters in air handling units possessing a substantial filtration efficiency towards all particle sizes down to 100 nm diameter and below is still the exception rather than the rule. Any existing passive ventilation is anyway accompanied by an unhindered intrusion of pollutants from outdoors.

A rigorous filtration of sufficient amounts of ventilation air is the most direct way of dealing with polluted indoor air, however it is not the most economical approach. An introduction of (localized) ventilation on demand and air cleaning on demand offers better prospects in this regard but depends on the availability of practical and reliable air pollution sensors. Only CO_2 sensors and motion sensors detecting human presence are currently used for enabling ventilation on demand in spaces like meeting rooms and school classes wherein many people reside. Reliable and robust particle sensors or gas (VOC, NO_x) sensors capable of measuring the (relatively very low) absolute gas concentration levels in polluted indoor air have up till now not become available in the market place at an acceptable price level.

The present paper discusses a UFP sensor that can be installed in air handling units and/or in separate indoor rooms. Its output signal can be used to adjust the ventilation and air cleaning strategy to existing needs in a more sophisticated and economical way than what has been possible up till now. Ideally, the UFP sensor is used to complement the information obtained from T, RH and CO_2 sensors and can be integrated in a building automation system.

Whenever the outdoor air has an unacceptable cleanliness level, it is desirable to avoid any natural ventilation and pass all mechanically supplied ventilation air through one or more filters to accomplish a sufficient degree of air cleaning prior to its release indoors. The novel embodiment of the electrostatically-enhanced particle filter presented in this paper can be of help to also accomplish the particle filtration step in a more energy-efficient way than what is achievable when conventional mechanical filters of similar size and performance are used.

EQUIPMENT

UFP sensor

All common particle sensors are currently optical sensors capable of detecting particles down to 300 nm diameter, the most expensive ones down to 100 nm. Because of their price (at least a few thousand Euro’s) and maintenance requirements, their use is limited to monitoring clean

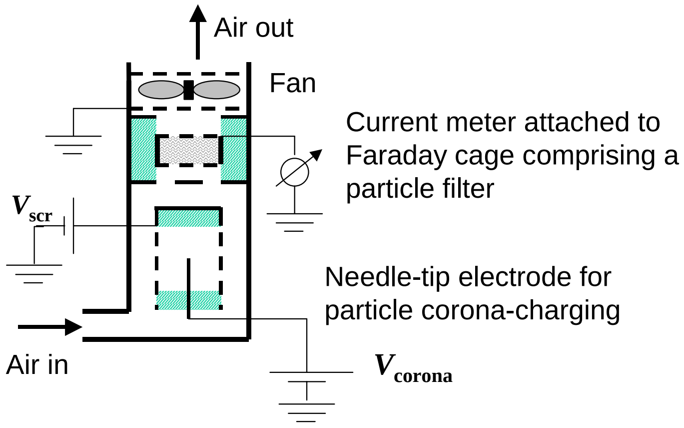

Figure 1:- Schematic design of the UFP sensor

room environments and professional air pollution measurements. Optical sensors are incapable of detecting particles smaller than 100 - 300 nm, even though most combustion-related ultra fine particles, and also cigarette smoke particles, are smaller than 100 nm.

To fill this technology gap, we realized an electrical UFP sensor that is particularly sensitive for detecting hazardous ultra fine particles down to sizes as small as 10 nm. A schematic design of the home-built UFP sensor is depicted in Figure 1. A small airflow ϕ is drawn through the sensor by means of a mini-fan situated atop the sensor. Airborne particles entering the UFP sensor are first charged via diffusion charging [6] with a corona discharge from a needle-tip electrode (set at V_{corona}) that is surrounded by a separate screen electrode whereupon a screen voltage $V_{scr} << V_{corona}$ is imposed. Subsequently, the charged particles are captured within a filter situated inside a conducting Faraday cage. A current meter attached to this cage records the amount of particle-bound charge that deposits inside the filter per unit time as a current I_{sensor}. I_{sensor} constitutes the sensor signal.

Because particles are charged via diffusion charging, one has for the average number of elementary charges "p(d$_p$)" that attach to a particle of diameter d_p the proportionality

$$p(d_p) \propto d_p \tag{1}$$

[6]. In practice, a particle size distribution $\frac{dN(d_p)}{d\ln d_p}$ is encountered in the ambient air wherein $dN(d_p)$ denotes the particle concentration for particles of diameter d_p. An integration of the particle size distribution over all particle diameters d_p yields the total airborne particle number concentration N_{total} (particles/cm^3) according to

$$N_{total} = \int_{d_p=0}^{\infty} \frac{dN(d_p)}{d\ln d_p} d\ln d_p \tag{2}$$

The sensor signal I_{sensor} relates to the ambient particle size distribution and the airflow ϕ (m^3/s) through the sensor according to

$$I_{sensor} = \int_{d_p=0}^{\infty} \phi p(d_p) e \frac{dN(d_p)}{d\ln d_p} d\ln d_p \propto \int_{d_p=0}^{\infty} d_p \frac{dN(d_p)}{d\ln d_p} d\ln d_p \tag{3}$$

$$\propto L_{total}$$

L_{total} (in units m/m^3) denotes the total particle length concentration, i.e. the total length of the string of particles that is created when all airborne particles within a unit volume would be lined up side by side. It is well known that in ambient air, the overwhelming contribution to both N_{total} and L_{total} comes from particles sized between 10 nm and about 200 - 300 nm, i.e. the combustion-derived UFPs. Larger particles ($\geq$ 1 µm) hardly contribute to both N_{total} and L_{total} but are almost exclusively responsible for all airborne particles mass M_{total} (µg/m^3).

The question is now what is learned from knowing L_{total}. It is generally believed that in as far as solid UFPs like soot particles are concerned, the relative health hazard H_{ufp} of inhaled UFPs relates primarily to the deposited UFP surface area $S \sim d_p^2$ in the deep alveolar region of the lung where gas exchange with blood occurs. In contrast with the upper head airways and the intermediate tracheo-bronchial part of the lungs, the alveolar region has significant difficulty cleaning itself from particulate deposits. The UFP surface carries carcinogenic substances like poly-cyclic aromatic hydrocarbons (PAH) and a long residence time of deposited UFPs in the alveolar region adds to their hazardousness. Other than the surface area d_p^2 of a lung-deposited UFP particle, an assessment of H_{ufp} must also take into account the alveolar deposition efficiency of inhaled UFPs as a function of d_p. Figure 2 shows the respiratory deposition efficiency of inhaled particles as a function of d_p in different parts of the airways (see e.g. ref. [6], Chapter 11). Concerning the alveolar region, it can be inferred from Fig. 2 that the alveolar UFP deposition efficiency is approximately proportional to $d_p^{-0.5}$ within the 10 – 300 nm particle size range. The relative health impact H_{ufp} then follows from

$$H_{ufp} \propto \int_{d_p=0}^{\infty} d_p^2 d_p^{0.5} \frac{dN(d_p)}{d\ln d_p} d\ln d_p = \int_{d_p=0}^{\infty} d^{1.5} \frac{dN(d_p)}{d\ln d_p} d\ln d_p \qquad (4)$$

which is more closely related to L_{total} than to N_{total} or M_{total}. Thus, to a first approximation, a measurement of $I_{sensor} \propto L_{total}$ with the UFP sensor can be used to approximately infer the health-hazardousness of the ambient UFP pollution level.

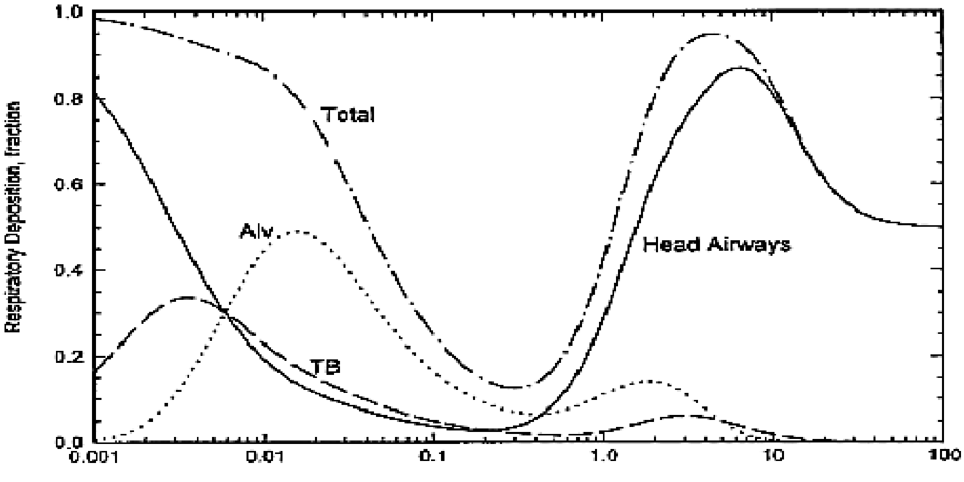

Figure 2:- Predicted total and regional deposition fraction of airborne particles in the human airways during nose-breathing with light exercise according to the International Commission on Radiological Protection (ICRP) deposition model (see e.g. ref. [6] Chapter 11). TB = tracheo-bronchial region; Alv = alveolar region. The total deposition fraction is the sum of the regional deposition fractions in the head airways, the TB region and the alveolar region.

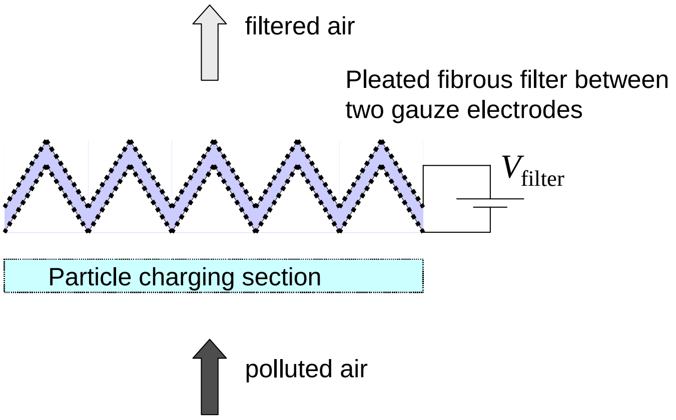

Figure 3:- Schematic design of the electrostatically-enhanced particle filter featuring an upstream particle charging section and a downstream particle filtration section.

Electrostatically-enhanced particle filter

To improve the ventilation air cleanliness, mechanical particle filters can be installed to try removing a substantial portion of airborne particles from air. The incurred pressure drop ΔP across these filters is directly proportional to the HVAC power required for air filtration. It is desirable to have filters of a given size that enable a desired air cleaning efficiency at a minimized power consumption. Figure 3 shows the schematics of a home-designed electrostatically-enhanced fibrous filter. A corona-charging unit is located upstream from the pleated fibrous filter and serves to provide all airborne particles with an electrostatic charge through local air ionization. Importantly, the pleated filter features a filter cloth that is sandwiched between two gauze electrodes possessing a carefully chosen conductivity. By imposing a voltage difference between the gauze electrodes, an electric field is set up across the filter cloth, which was experienced to markedly improve the efficiency with which charged particles can be filtered from air.

RESULTS

UFP sensor

Some typical UFP sensor recordings in indoor air as a function of time are shown in Figure 4 for the extremes of (pre-filtered) laboratory air and of cabin air (pre-filtered by an ordinary cabin filter) in a driving automobile. In all cases, the UFP sensor signal and thus the indoor UFP concentration varies significantly in the course of time, presumably in parallel with the outdoor UFP concentration variation. However the rate of change of the UFP sensor signal in laboratory air is relatively limited whereas fast variations are encountered inside a car cabin due to the rapidly changing proximity of (the exhausts) of other cars. It is evident from Figure 4 that the measured I_{sensor} inside a car and thus the cabin UFP pollution level can be up to 100 times higher than in the “clean” laboratory environment. This is evidence of the relative seriousness of the cabin air pollution level, a situation that most people are not aware off.

The air sampling rate of our UFP sensor $\phi = 0.5$ liter/min while the sensor signal I_{sensor} is measurable down to a sensitivity of about 1 – 2 fA within a measuring range 0 – 10 pA. This approximately conforms to a measuring sensitivity of the UFP number concentration of 1000 /cm^3 for UFPs sized in the $d_p = 10 - 300$ nm diameter range. The average UFP diameter in ambient air is usually between 30 and 70 nm. A UFP concentration as low as 10^3 /cm^3 is encountered only in very clean air (e.g. high in the Swiss Alps). In ordinary sub-urban air,

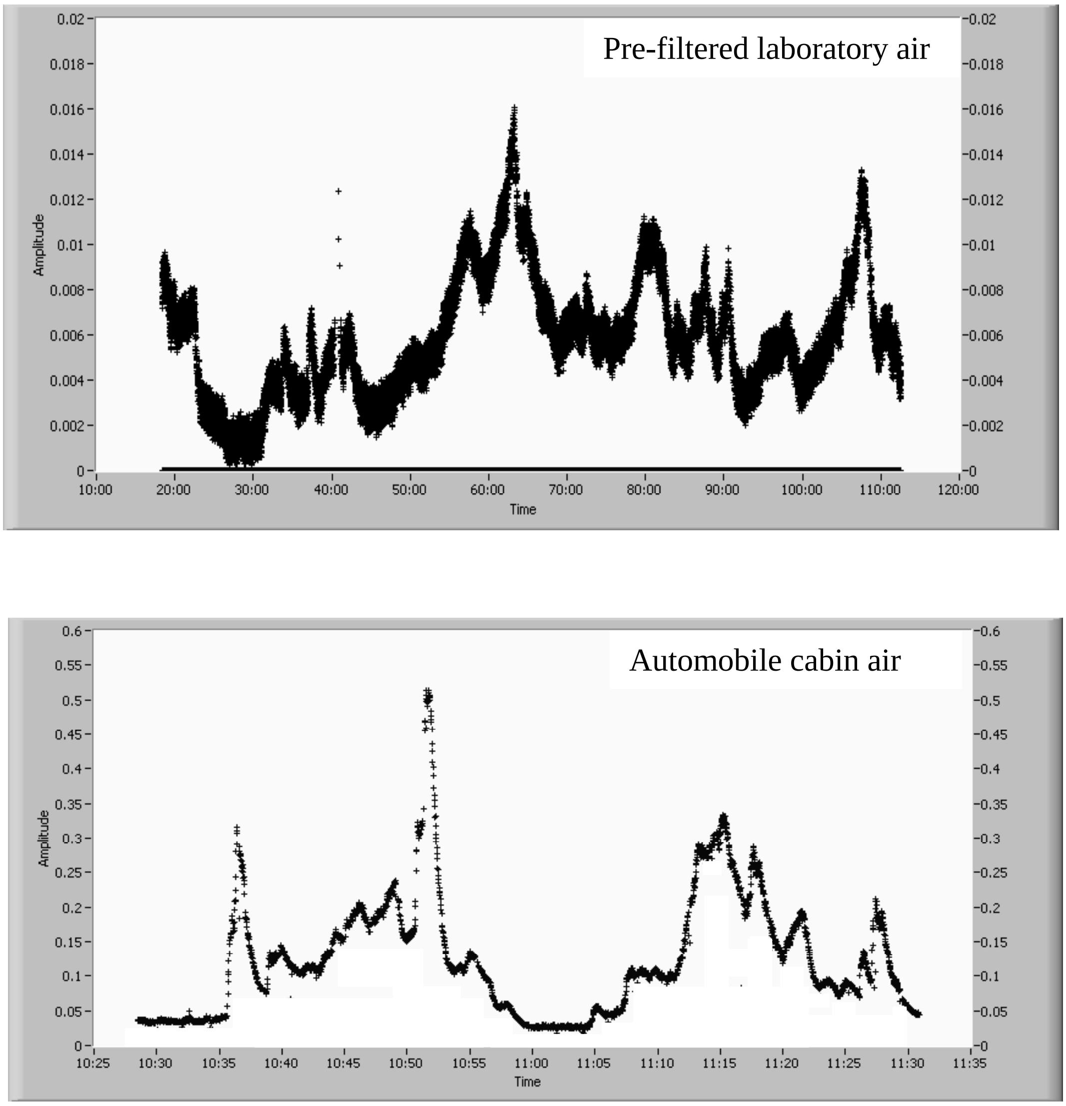

Figure 4:- Measured amplitude of the UFP sensor signal (in units pA) as a function of time (in hours) in a laboratory environment and in the cabin of a driving car.

UFP concentrations are typically close to 10^4 particles/cm^3 (leading to $I_{sensor} \approx 0.03$ pA). Near busy roads, this can rise up to $5*10^4$ particles/cm^3 and up to $5*10^5$ inside the cabin of a car stuck in a traffic queue. The UFP sensor is therefore able to readily discriminate between clean air, moderately polluted air and seriously polluted air.

Electrostatically-enhanced particle filter

An electrostatically-enhanced fibrous filter designed according to the schematics shown in Fig. 4 was realized and subjected to several filtration efficiency tests both in the absence and presence of electrostatic enhancement. For this purpose, the particle size distribution for particle diameters from 10 – 300 nm was measured with a Scanning Mobility Particle Sizing system (Type 5403, Grimm GmbH, Germany) upstream and downstream of the filter at various air flows through the filter. The results are shown in Figure 5.

In the absence of electrostatic enhancement, the filter behaves as an ordinary mechanical filter with a filtration performance that approximately conforms to that of a EU 6 filter, characterized by a poor filtration performance with respect to UFPs larger than 50 nm.

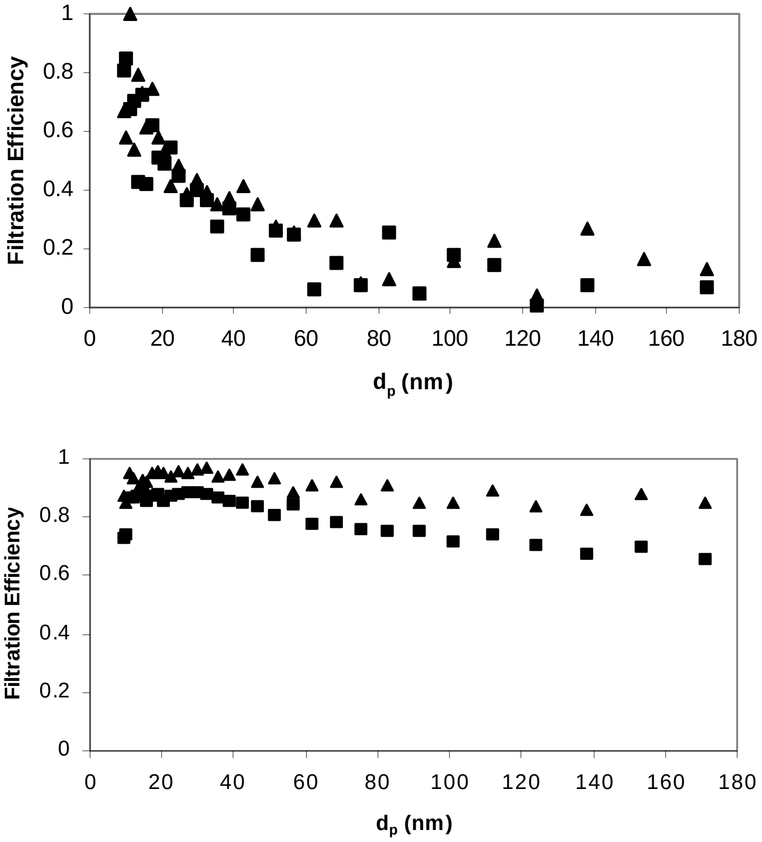

Figure 5:- Measured filtration efficiency of a particle filter before electrostatic enhancement (top) and after electrostatic enhancement (bottom) as a function of the UFP diameter d_p. The superficial airflow speed was set at either 1 m/s (▲) or 2 m/s (■) while the electrostatic enhancement involved both particle charging and the set-up of an electrostatic field E_{filter} = 1 kV/mm across the depth of a fibrous filter cloth.

For particles sized between 100 nm and 200 nm, the filtration efficiency does not exceed 20% at an apparent airflow speed of 1 – 2 m/s through the filter cassette. In the presence of electrostatic enhancement wherein the particles are electrostatically charged and subsequently passed through a fibrous filter across which a field strength $E_{filter} \approx 1$ kV/mm is applied, the filtration efficiency significantly increases up to 70 – 80% for 100 – 200 nm sized particles. Note that this efficiency increase is accomplished at a constant power consumption, airflow speed, and size of the filter cassette. The specific power consumption required for airborne particle charging and filter polarization only amounts to a few W for an air flow of several hundred m^3/hr and is therefore negligible with respect to the total HVAC power consumption.

DISCUSSION

The described UFP sensor yields a real-time output signal proportional to the ambient UFP pollution level according to a metric that approximately corresponds with the relative health-hazardousness of the UFP pollution level. At any locality where the dose of air pollution is received from a more-or-less constant set of pollution sources (e.g. automobile traffic) in the course of time, the UFP pollution level may be expected to at least roughly reflect the total airborne gaseous/particulate pollution level. The UFP sensor readily distinguishes clean air from moderately or seriously polluted air and can be used for assessing pollution levels in outdoor and indoor air. Because the local outdoor and indoor air pollution vary strongly in time and place, it is convenient to continuously monitor these pollution levels with UFP sensors in order to acquire pollution-related decision factors for optimizing the ventilation strategy.

In case all ventilation air is received from a mechanical air handling unit that is supplied with an air filter, it is recommended to position UFP sensors directly downstream of the filter and/or in the indoor enclosure itself away from the supplied ventilation air flow. This allows for a monitoring of the residual UFP pollution level in the supplied ventilation air and/or in the indoor air itself, respectively. Electronic feedback from the UFP sensor, preferably in combination with feedback from other sensors (T, RH, CO_2, human presence), can then be used to enable ventilation on demand, to adjust the total ventilation air flow and/or the ratio between supply air and return air such as to minimize the absolute indoor pollution level while retaining comfortable and productive indoor conditions in an energy-efficient way. The application of an electrostatically-enhanced particle filter in the air handling unit instead of a conventional mechanical filter will help to further minimize the required power consumption necessary for creating a healthy and comfortable indoor air quality.

In case the ventilation air is a mixture of naturally supplied ventilation air and mechanically supplied filtered ventilation air, it is recommended to continuously monitor the UFP pollution both outdoors and indoors. Received sensor signals can then be used to adjust the ratio between natural ventilation and mechanical ventilation either automatically or manually, aiming to minimize the indoor pollution level in an energy-efficient way under all environmental circumstances. It is obvious that the recommended ventilation strategy will usually be the outcome of a judiciously chosen compromise.

Various additional application modes of UFP sensors can be readily construed and applied in homes, offices and cars. A common aspect is always that the very presence of UFP sensors allows for a direct visualization of the UFP pollution level. Except through the application of professional expensive instrumentation, UFP pollution visualization has up till now not been possible and can therefore be of much help in both raising human awareness with respect to the pollution level in inhaled air and in reducing human exposure to indoor air pollution.

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