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CONTROL STRATEGIES FOR SUBMICROMETER PARTICLES INDOORS: MODEL STUDY OF AIR FILTRATION AND VENTILATION

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ABSTRACT

The effect of air filtration, ventilation, air mixing and the enclosure volume on the particle concentration levels indoors were investigated and the results of the investigations are presented in this paper. Using a simple one zone mathematical model, particle concentration indoors was predicted for several indoor an outdoor conditions representing various scenarios likely to occur in naturally and mechanically ventilated buildings. The effects were studied for static and dynamic conditions, which were defined by the time dependency of input parameters.

The evaluation of the effects of the above factors was conducted for a hypothetical building representing an office type of indoor environment with input parameters based on real world data. While the quantitative results of the evaluation are building and conditions specific, using a broad range of input parameters in the presented simulations provided qualitative conclusions which are generally applicable.

Depending on the I/O conditions two main remedial strategies are suggested. For the conditions with high particle concentration outdoors, it is recommended to reduce the amount of outdoor air delivered indoors. The outdoor air flowrate could be decreased for example, by varying the speed of supply air fan, or by controlling the dampers in systems return air. In all these cases consideration should also be given to the magnitude of the airflow and its effect on thermal comfort and on the minimum outdoor air required for occupants.

For the conditions where the indoor concentration of particles is high due to the operation of an indoor source, it is recommended to increase the amount of outdoor air delivered indoors and to reduce the amount of return air.

Air filtration and ventilation reduce the level of particle concentrations indoors, with the overall effect depending on efficiency, location and the number of filters applied.

Consideration should be given to indoor environments with imperfect mixing, as a local build-up of particles could occur. The effect of room volume on particle concentration level indoors is insignificant.

The assessment of IAQ for specific, user-defined conditions, could easily be calculated by the model, which is available in spreadsheet format on the web side www.xxxxxxxxxxxx.

KEYWORDS ventilation, filtration, submicrometer particles, concentration, model, HVAC

INTRODUCTION

Several epidemiological studies {Schwartz and Markus 1990; Pope, et al. 1992; Dockery, et al. 1993; Dockery and Pope 1994} linked air pollution-related health problems to fine and ultra fine airborne particles. Fine particles are usually defined as those with aerodynamic diameter smaller than 2.5 micrometer (where $PM_{2.5}$ fraction is mass concentration of these particles) while ultrafine, as those that are smaller than 0.1 micrometer. There are indications that particle number rather than mass may be a more important factor when health implications are considered {Department of Health Committee on Medical Effects of Air Pollutants, 1995; Peters et al. 1997}.

All combustion sources, such as motor vehicle traffic, industrial combustion processes, burning, cooking, heating and tobacco smoking generate large quantities of fine and ultra fine particles. Recent studies indicate that in an urban environment more than 80% of particles in terms of number, are smaller than 0.1 μm {Morawska et al. 1996a; Morawska et al. 1998; Buzorius et al. 1999}. Smaller particles can penetrate deeper into the respiratory tract and therefore have higher potential to induce health effects than larger particles. The increased attention to fine airborne particles resulted in the $PM_{2.5}$ standard introduced recently by the US EPA {US EPA 1997}.

People spend most of their time indoors, at their homes, work and in transport. The provision of good indoor air quality (IAQ) in these environments is thus necessary to minimise exposure to airborne pollutants. More than 90% of the Australian workforce works in indoor environments with more than 50% of the workforce being employed in office environments. WHO estimated that 30% of new and remodelled office blocks show signs of sick building syndrome and that 10-30% of occupants are affected {Gilbert et al. 1993}.

For office and other similar work-related environments, hospital, schools etc., the main source of pollutants is often outdoor air. These premises are usually ventilated mechanically with an HVAC system, providing air ventilation and filtration.

In residential houses indoor sources such as tobacco smoking, gas combustion (heaters, gas stove) and cooking are the primary sources in addition to outdoor air. Most residential houses in Australia are ventilated naturally without provision for air filtration.

The control of contaminants indoors is achieved by one of the following methods: source control, dilution control, or removal control. Although source control is preferred, this option is not always available. Thus, ventilation and air filtration are the main remedial actions applied to reduce exposure to airborne contaminants indoors.

Ventilation

Generally ventilation represents a dilution control of indoor pollution, ie., contaminated indoor air is diluted or displaced with “clean” outdoor air. The effectiveness of the process is important as poor ventilation efficiencies can lead to local build-up of contaminants {Rask and Sun 1989}. Ventilation performance depends on room geometry, ventilation method applied and on its operating conditions, as well as on the location and strength of the sources and the types of contaminants generated {Yamamoto et al. 1994}. Most frequently it is assessed using the age-of-air method {Sandberg 1983}, or as in this paper, by the air mixing factor {Chung and Dunn-Rankin 1998}. Perfectly mixed air has a mixing factor equal one.

Studies of pollutant dynamics in indoor air are commonly based on the approximation that the air within a room is uniformly distributed and that the pollutants are mixed instantaneously {Shair and Heitner 1974; Nazaroff and Cass 1986; Baughman et al. 1994}. This is usually justified for cases with strong internal motion, such as in mechanically ventilated buildings {Persily et al. 1993; Jamriska and Morawska 1996}.

A quantitative measure of the ventilation process is ventilation rate or air exchange rate, defined as the ratio between the outdoor air flowrate and the effective volume of ventilated space. A study on ventilation rates for residential houses in Australia, with mild to warm climate found that the average air exchange rate (AER) was 26.3 h^{-1} {Biggs et al. 1986}. This is a relatively high value in comparison with values reported from similar studies conducted in Canada and Sweden, where the average ventilation rate was 4.4 h^{-1} and 3.7 h^{-1}, respectively. The implication of these finding is that the effect of outdoor air could be more significant for naturally ventilated dwellings in warmer than in cooler climates. The ventilation rate was monitored in 14 office buildings in the USA over the period of one-year {Persily 1989}. The average air exchange rate for all the buildings was about 0.9 h^{-1}. Similar results were reported by {Jamriska and Morawska 1996} with a ventilation rate of about 0.8 h^{-1}, measured in an office in Brisbane.

Air handling systems (AHS)

Two basic types of air handling systems and associated controls are commonly applied in mechanically ventilated buildings: constant volume (CAV) and variable air volume (VAV) systems. In the CAV system the supply fan always moves the same amount of ventilation air and the temperature of the supply air (SA) is varied to meet the space-conditioning load within the building. In these systems the amount of outdoor air (OA) is controlled by varying the position of the intake, return and exhaust air dampers. In a variable air volume (VAV) system the SA temperature is kept constant and the SA flowrate into the building is varied to meet the space-conditioning load. VAV systems are more common in newer buildings due to their reduced energy consumption and the ability for better control of local environmental conditions.

Filtration

Mechanical filtration systems are intended to limit the introduction of pollutants from outdoors to indoors. The efficiency of such systems generally depends on the filter properties and aerodynamic properties of filtered particles. The efficiency of filters varies from 5-40% for low efficiency filters, such as dry media filters, panel and bag filters to over 99% for HEPA filters. Electrostatic precipitators represent medium to high efficiency filters, with the performance in the range from 60 to 90%. In most cases the selection of filters installed in HVAC systems depends on the type of indoor environment, outdoor and indoor sources, demand on the level of reduction of pollutant concentrations and the cost associated with purchase, operation and maintenance of the system. Not only the filters, but the whole HVAC system contributes to particle reduction, due to particle losses on the cooling/heating coil and other parts of the AHS. The most commonly used filters installed in office type buildings in Australia are dry media, low to medium efficiency filters and electrostatic filters {Morawska and Jamriska, 1997}.

OTHER MECHANISMS AFFECTING PARTICLE CONCENTRATION INDOORS

Surface deposition and coagulation

Particle number concentration is continuously reduced due to surface deposition and coagulation. The rate of change is characterised by particle loss rate or deposition velocity {Nazaroff et al. 1993}. Surface deposition of sumbicrometer particles is dominated by Brownian and turbulent diffusions and thermophoresis and the effect of gravitational force on these particles is negligible {Jamriska and Morawska, 1999c}. The effect of Coulomb forces on particle loss from the air can also be neglected as in modern buildings only a few surfaces are charged (Schneider et al. 1999}.

The coagulation rate depends on particle size and concentration. For the type of indoor environments and concentration conditions considered, both of these mechanisms are less significant than ventilation and air filtration {Jamriska and Morawska, 1999; Wexler et al. 1994}.

Resuspension

{Thatcher and Layton 1995} concluded that resuspension decreases as the optical particle diameter decreases, with an apparent resuspension threshold of about 2 micrometers. Thus, for fine particles resuspension is not an important source that would contribute to their concentrations indoors. Similarly, {Raunemaa et al. 1989} concluded that the particle reemission for an office building with an HVAC system was insignificant.

Building Penetration Factor

Due to their very small size, ultra fine particles exhibit almost gaseous properties and the protection effect of the building envelope is limited. Studies conducted by {Thatcher and Layton 1995; Ozkaynak et al. 1996; Lange 1995} indicated that the materials of the buildings filter fine particles penetrating through them only negligibly, with the penetration factor close to one.

Experimental studies and mathematical models on indoor/outdoor (I/O) relationship

Numerous studies have been conducted in order to assess and predict the concentration levels of pollutants indoors. Studies on the I/O relationship were conducted by {Andersen 1972; Alzona et al. 1979}; Dockery and Spengler 1981; Raunemaa, et al. 1984; Koutrakis et al. 1992; Weschler et al. 1996} and others, to name just a few. While most of the studies have focused on larger particles and/or gaseous pollutants, less work has been done on the I/O relationship for fine particles.

Assessing human exposures necessitates extensive indoor monitoring, which can be expensive and time consuming. Mathematical models could be used to assess the exposure and are useful for implementing control strategies. The models vary from very simple to very complex.

One zone models focused on particle mass, targeting various aspects of the I/O relationship and considering only a limited number of mechanisms affecting particle characteristics were developed by {Dockery and Spengler, 1981; Sexton et al. 1983; Raunemaa, et al. 1984; Yamamoto et al. 1987; Kulmala et al. 1988; Raunemaa et al. 1989; Ekberg 1994; Ekberg 1996; Jamriska et al. 1998; Fogh et al. 1997; Kulmala et al. 1999}. Multi-zone models with more enhanced features were developed for example by {Sparks et al. 1989; Evans 1996; Schneider et al. 1999} and others.

Sophisticated models incorporating particle dynamics and chemistry processes were developed by {Gelbard and Seinfeld 1980; Nazaroff and Cass 1986; Nazaroff and Cass 1989; Whitby McMurry 1997}.

Most of these models are based on the particle mass balance equation, and have been validated only for larger particles. The prediction of the fate of fine and ultrafine particles, which have negligible mass in comparison with larger particles, is usually not available.

The selection of a model for IAQ assessment depends on the specific application and the accuracy required. The complex models require large sets of input parameters that are often not available and thus carry a high degree of uncertainty. The other issue to be considered is model validation, which is more difficult for complex models than for the simpler ones. While sophisticated models could potentially provide more accurate answers to the specific questions, the use of simpler models for general assessment of IAQ and associated parameters under commonly occurring conditions, could be more practical.

The objective of this work was to investigate the effects of air ventilation and filtration on submicrometer particle concentrations indoors. The problem was studied using a simple mathematical model simulating the time evolution of particle concentration indoors.

The evaluation of the effects was conducted for a hypothetical building representing an office type of indoor environment. Simulations were conducted for several indoor/outdoor scenarios for static and dynamic conditions. The input parameters were related to ventilation (air flowrates, air mixing), filtration (filter efficiency), particle losses due to deposition and coagulation, and effective volume of the space. Variation of the parameters over a range of values relevant to real world situations provided quantitative and qualitative assessment of the role of various factors on IAQ.

The simulation of the evolution of particle concentration indoors presented here was conducted using a simple model developed previously and extensively validated with experimental data from chamber and field studies. The effect of filtration, ventilation and other parameters on the evolution of submicrometer particles in terms of the number and mass concentrations was comprehensively assessed and is discussed in this paper.

The study provides a general assessment of the trends in IAQ under conditions likely to occur in real world environments. Based on the findings, remedial strategies implementing the ventilation and air filtration mechanisms were identified and are recommended to achieve and maintain good air quality indoors.

MODEL

A one-zone mathematical model predicting the evolution of total particle concentration indoors was used for the simulations. The model is based on the number balance equation and assumes that the changes in particle concentration due to chemical reactions and particle dynamics are negligible and that the pollutants are perfectly mixed {Yamamoto et al. 1987; Nazaroff and Cass 1989; Kulmala et al. 1999}. These assumptions are valid for most of the work related non-industrial environments.

Figure 1 presents the schematic diagram [OF WHAT?] developed for an enclosed space with an HVAC system and the parameters included in the model. The diagram could also be applied for a naturally ventilated space.

The relevant variables affecting particle concentration indoors are the outdoor concentration levels, air flowrates, the filtration effect of an HVAC system, indoor generation rates of particles, particle losses due to surface deposition and coagulation, aerosol mixing and the effective volume of the enclosure. The particle number balance equation incorporating these mechanisms represents a first order partial differential equation expressed as:

$$\frac{dC}{dt} + \alpha C = \beta \tag{1}$$

where

$$\alpha = \frac{k}{V}\left(-Q_{RA\_in}P_{2,3,,8} + Q_{RA} + Q_{G.Exh} + Q_{L.Exh} + Q_{Exf} + Q_{RCL}\varepsilon_{RCL} + V\lambda\right) \tag{2}$$

$$\beta = \frac{C_{OA}}{V}\left(Q_{OA}P_{1,3,8} + Q_{LMA}\left(1-\varepsilon_{LMA}\right) + Q_{Inf}P_{Bldg}\right) + \frac{\sum_i G_i}{V} \tag{3}$$

where

C-indoor concentration, C_{OA} - outdoor air concentration; V- effective volume of the enclosure; k – mixing factor; G_i – emission rates of different indoor sources; λ – particle loss rate due to surface deposition and coagulation; P_{Bldg} – penetration factor of the building envelope; Q_i, ε_i and P_i are air flowrates, filter efficiency and penetration as presented in Figure 1, respectively. The $P_{n1,n2,...nx}$ denotes the overall penetration through filters $n1,n2$ ..nx, calculated as $P_{n1,n2,...nx}$ = (1-ε_{n1}).(1-ε_{n2})…(1-ε_{nx}).

If λ and G_i are time independent the general solution to Eq 1 is:

$$C(t) = C_o e^{-\alpha t} + \frac{\beta}{\alpha}\left(1 - e^{-\alpha t}\right) \qquad (4)$$

For λ and G_i time dependent the solution to Eq 1 is expressed as:

$$C(t) = C_o e^{-\alpha t} + \int_0^t e^{-\alpha t} \beta dt \qquad (5)$$

where C_o is initial indoor particle concentration at time $t=0$.

The first term on the right-hand side of Eq 4 reflects the decay of the initial number concentration due to ventilation, air filtration as well as of surface deposition and coagulation; the second term reflects the time evolution towards the steady-state concentration $C_\infty = \beta/\alpha$. The time evolution of other aerosol characteristics such as size distribution, count median diameter etc., have not been investigated, however, for the typical conditions occurring in most indoor environments, these parameters do not change significantly (Jamriska and Morawska 1999).

The model has been validated in laboratory and field studies showing very good agreement between measured and predicted data {Jamriska et al. 1998; Jamriska et al. 1999b}.

METHODOLOGY

The effect of ventilation, air filtration and other mechanisms on the evolution in submicrometer particle concentration indoors was investigated theoretically by applying the presented mathematical model to a range of test conditions. The simulations were conducted for a hypothetical building representing a general office type indoor environment with an HVAC system. The input parameters used were based on previously conducted studies in real buildings {Jamriska and Morawska

1996}. The values of the parameters, such as ventilation rate, filter efficiency etc. varied within a range likely to be encountered under real world conditions.

Particle concentration indoors $C(t)$ was calculated from Eq 4 for a series of time steps. Depending on the time variation of the input parameters the simulation was conducted for two scenarios: static and dynamic. The static scenario assumes that the input parameters are time independent (constant) within the whole interval of prediction. Under the dynamic scenario the input parameters are constant only within one time step. For both scenarios the calculated concentrations indoors $C(t_i)$ at the end of the interval t_i were used as the input for initial concentration $C_o(t_{i+1})$. The static simulations were conducted for intervals up to 6 hours, with time resolution of 5 minutes. The dynamic simulations were conducted for a 24 hour period in 30 minutes time steps.

The time evolution in particle concentration could be calculated for both number and mass. In the presented study the mass concentration was recalculated from particle number concentration and size distribution, assuming particle sphericity and known particle density {Jamriska et al. 1999a}. Application of the reverse procedure, ie. determination of the evolution in particle number concentration from experimentally determined evolution in particle mass is more difficult for submicrometer particles. This is related to the fact that the mass of submicrometer particles is very low. To provide a relatively accurate link between particle number and mass concentration would require high resolution in particle mass classification according to particle size.

Conditions under which the evolution of particle concentration indoors was predicted.

Depending on the values of initial indoor and outdoor particle concentrations, four general conditions (*A*,*B*,*C*,*D*) were considered for static scenario simulations (Table 1).

The condition A ($C_{OA}>>C_o$) represent a situation where the outdoor concentration is relatively high and C_o represents an average ambient air concentration level {Morawska et al. 1998}. This may occur for example in a building without any significant indoor sources operating, equipped with an HVAC system and located in a relatively polluted urban environment. Under conditions B and C, both the indoor and outdoor particle concentrations are of the same level (C_{OA}~C_o). The situation is likely to occur in naturally or mechanically ventilated buildings without air filters. Conditions B and C represent relatively high and average ambient air particle concentrations, respectively. Condition D ($C_{OA}<<C_o$) is a case invert to condition A, with relatively high particle concentration indoors and an average concentration outdoors. This may represent a situation where a significant indoor source is present, such as smokers, cooking or combustion appliances.

The input parameters used for the simulation under dynamic conditions were based on real world measurements of particle concentration outdoors in an urban environment. The data were collected as a part of a three week long monitoring study conducted near a busy road, in the inner part Brisbane, Australia. The details of the study are presented elsewhere {Morawska et al. 1998; Jamriska et al. 1999a}. The main source of submicrometer particles was traffic emissions with the concentration outdoors showing diurnal variations. The concentration level peaked during traffic peak hours, in the morning and in the afternoon (Figure 2a).

The most common indoor source of submicrometer particles is tobacco smoke and combustion process such as gas burning, heating or cooking. For the office type, and other non-industrial work- related environments, these sources are usually not present (Nazaroff xxx). The effect of people presence and their activities (walking, working, etc) on particle generation was estimated to be on average of 4.17×10^4 particles s^{-1}.per person {Salvigni et al. 1996}, assuming a constant presence of 100 people indoors.

The effect of surface deposition and coagulation was incorporated into the simulations through the overall loss rate parameter λ. This parameter was calculated from the deposition velocity v_d and the surface to volume ratio as $\lambda = v_d * S/V$ {Nazaroff et al. 1993}. The values of v_d were determined experimentally {Jamriska and Morawska, 1999c; Nazaroff et al. 1990} and the S/V ratio was estimated as 3 m^{-1} {Wallace 1996}. These parameters are listed in Table 1.

Since the focus of this work was on submicrometer particles in an office environment, it was assumed that the re-emission factor was zero {Thatcher and Layton 1995}.

IAQ is affected by air mixing. The measure of this process is expressed as mixing coefficient k, determined using the tracer gas decay technique from the relationship: $ln(C/C_o) = -VR.k.t$, where C and C_o are indoor concentrations at time t, and $t=0$, respectively; VR is ventilation rate [h^{-1}], and k *is* mixing factor {Chung and Dunn-Rankin 1998}. For ventilation and air filtration effects assessment perfect air mixing conditions were assumed ($k=1$). The effect of imperfect air mixing on particle evolution indoors has also been simulated [WHERE].

The response time

To assess the rate of change of particle concentration indoors, two parameters were introduced. They are denoted as $t_{resp}(0.5C_{\infty})$ and $t_{resp}(0.9C_{\infty})$, and defined as time intervals required for the indoor concentration to evolve from the initial value C_o to 50% and 90% of the steady-state concentration C_{∞}, respectively.

The presented simulations were conducted for various operational settings of the HVAC system representing both CAV (*CASE 1*) and VAV (CASE 2,3,4) systems under the test conditions *A,B,C,D*. Table 2 summarises the input conditions and the AHS flowrate regimes used for static modelling.

RESULTS AND DISCUSSION

The effect of the following mechanisms was considered in assessing the evolution of particle concentration indoors: a) ventilation; b) air filtration; c) air mixing, and; d) the effective volume of the enclosure. Figure 1 presents a schematic diagram of the HVAC system and Tables 1 and 2 present the input parameters and annotation used.

THE EFFECT OF VENTILATION

The evolution of particle concentration for an indoor environment ventilated by an AHS with constant supply and variable outdoor and return air flowrates.

CASE 1A

Figure 2a presents the evolution of particle number and mass concentrations indoors for the static scenario and for average particle concentration indoors but high concentration outdoors.

In this case, particle concentration indoors is determined by the fraction of outdoor air in supply air. Parameter *R1*, defined as the ratio between outdoor air and supply air flowrate $R1=Q_{OA}/Q_{SA}$, is used to quantify this fraction. Increasing the amount of OA delivered indoors increases the concentration significantly. For an AHS operating at 100% OA mode the $C_{\infty}(R1=1)$ was 2.44×10^4 particles cm^{-3} (109 $\mu g\ m^{-3}$), which represents 65% of the C_{OA}. These values correspond to the AHS filtration efficiency, which was approximately 35%. For a building with lower filtration efficiency or no filtration system installed the indoor concentration would be higher.

For the system operating under 100% recirculating mode, the $C_{\infty}(R1=0)$ was about 110 particle cm^{-3} (0.5 $\mu g\ m^{-3}$), or less than 1% of C_{OA}. The $C_{\infty}(R1=1)$ was approximately three times higher than the initial concentration C_o.

For the system operating under usual operational mode (*R1*=0.1) the steady-state concentrations are approximately 5.9×10^3 particle.cm^{-3} (26.6 $\mu g\ m^{-3}$), which represents 16% of the C_{OA}. Thus, the range of steady-state concentrations could vary significantly, and in the presented case the variation was almost two orders of magnitude. The steady-state concentration $C_{\infty}(R1=1)$ is 217 times the value of $C_{\infty}(R1=0)$ *[WHERE IS THIS VALUE FROM? IN ANY CASE SHOULD BE ROUNDED].*

The response time is inversely dependent on the Q_{OA}. For the discussed condition A and also for the conditions B, C, D, the $t_{Resp}(0.9C_{\infty})$ varied between 20 min (*R1=1*) and 60 min (*R1=0*), and $t_{Resp}(0.5C_{\infty})$ varied between 5 min (*R1=1*) and 14 min (*R1=0*). This indicates that a sudden increase in outdoor concentration may result in a rapid negative impact indoors [WHAT IS MEANT BY NEGATIVE IMPACT?].

For an AHS operating at 20% of OA the steady-state concentration $C_\infty(R1=0.2)$ is approximately the same as the initial indoor concentration C_o.

For the discussed scenario, the strategy recommended to minimise the risk associated with outdoor pollutants would be to reduce the amount of OA delivered indoors. To be efficient, this strategy would require continuous monitoring of particle concentration outdoors and a relatively fast response in changing the operational parameters of the ventilation system.

CASE 1B

Figure 2b presents the simulated evolution of particle concentration indoors for condition B (high particle concentrations indoors and outdoors). The indoor concentration is rapidly decreasing in time due to the filtration effect for all simulated conditions ($0 \leq R1 \leq 1$).

The steady–state concentrations C_∞ are approximately the same as in *Case 1A*. This indicates that in the long term (one to two hours) the concentration of OA and the filtration efficiency of the HVAC system are the determining factors for IAQ. The effect of initial concentration C_o is more significant in the short term. The concentrations $C(t_{res}0.5C_\infty)$ were higher than in *CASE 1A*, ranging from 51% of C_{OA} ($R1$=0) to 83% for full OA mode ($R1$=1).

The recommended strategy for a CAV system under test condition B would be to reduce the amount of OA in SA, similarly as in *Case 1A*.

CASE 1C

The predicted evolution of particle concentration indoors for scenario C is presented in Figure 2c. As both C_{OA} and C_o, have the same values, the case is similar to *CASE 1B.* The concentration indoors is decreasing with an increase in *R1* values, reaching the steady-state concentrations of $3.9\text{x}10^3$ particle.cm^{-3} for *R1*=0 and $6.2\text{x}10^3$ particle.cm^{-3} for *R1*=1. Thus, in terms of predicted indoor concentration, the values were lower than in *Case 1B*, however, the relationship between ventilation parameters and the concentration levels indoors was the same. The most dominant parameters in this case are C_{OA} and Q_{OA}.

The recommended strategy for a CAV system under test condition C would be to reduce the amount of OA in SA.

CASE 1D

The simulated time evolution of particle concentration for condition D ($C_{OA} << C_o$ high) is presented in Figure 2d. The initial indoor concentration C_o was the most dominant parameter affecting the evolution of particle concentration. The trend in particle concentration could be analysed in two time intervals. In the first time interval the reduction is more rapid for ventilation conditions of larger R1 values. This implies that the AHS delivering larger amount of OA indoors are more efficient in reducing particle concentration indoors. This is due to the high value of C_o in comparison with C_{OA}. Thus, the reduction strategy for this situation would require increasing the Q_{OA} for a certain period of time after a sudden increase in concentration indoors occurred, until the pollutant concentration indoors is reduced to the level comparable with C_{OA}.

In the second time interval the situation reverses and evolution of indoor concentration follows the same pattern as observed for conditions A, B and C, ie the reduction in particle concentration is more rapid for the ventilation conditions with reduced amount of OA. In the presented scenario, the delimiting interval was approximately 45 minutes [WHAT WAS THE FIRST INTERVAL AND WHAT THE SECOND?].

Thus, for *Case1D* the most effective and rapid method to reduce particle concentrations indoors would be to operate the AHS at the full OA mode with minimum amount of RA. When the pollutant levels indoors are comparable to the level outdoors, the HVAC could be returned to its usual operational mode.

The evolution of particle concentration for an indoor environment ventilated by an AHS under variable SA flowrates

CASE 2

This case represents a VAV system with a constant fraction of OA in RA. Different operational conditions in terms of the RA flow are characterised by parameter *R2*, defined as $R2=Q_{RA}(actual)/Q_{RA}(rated)$. The values of *R2* and corresponding *VR* are listed in Table 2.

The simulated evolution of particle concentrations showed similar trends as for the *Cases 1A-D,* for $R1=0.1$ (Figures 2a,b,c,d). The concentration indoors decreased with time for all the investigated conditions. The decrease rate in concentration was faster for larger *R2* values, ie. for higher values of Q_{RA} (and thus also Q_{SA} values). This is caused by an increased effect of air filtration, since for conditions of larger *R2* values the recirculation of air through the SA filter increases (increased number of air passes through the filter).

The steady-state concentration for each individual *(A,B,C,D)* test condition was determined by C_{OA} and filtration efficiency of the HVAC system. The *RA* flowrate did not significantly affect the C_∞ ie, the steady-state concentration was almost independent of the *R2* values.

The response time $t_{resp}(0.5C_\infty)$ was between 7 min ($R2$=2) to 45 min ($R2=0.25$), and for normal operational conditions ($R2=1$), it was approximately 12 minutes. This means that the AHS, operated under very low Q_{SA} could exhibit a relatively long response time.

It could be concluded that, for the AHS operated at variable SA flowrate, with the Q_{OA} set as a constant fraction of the Q_{RA}, an increase in Q_{RA} (and thus also Q_{SA}) will decrease the particle concentration levels indoors. With an increase in Q_{RA} the response time is reduced and the reduction rate increased, ie. the concentration indoors will decrease quicker and more rapidly [THESE TWO MEAN THE SAME]. A reduction strategy for this operational mode of an AHS would require increasing the amount of RA recirculated indoors.

CASE 3

In this mode the VAV system operates with a constant Q_{OA} (rated value) and varying Q_{RA}. The operational conditions are characterised by parameters *R1, R3=R2 (*Table2.)

For condition A the concentration indoors follows patterns similar to *Case 1A* (Figure 2a). The concentration increases for *R3<0.11* and decreases for R3>0.11. This is due to the significantly higher C_{OA} in comparison with C_o.

For the simulations under conditions B,C and D, the indoor concentration decreases for all values of R3 and follows trends similar to *CASE 1B*. The effect of Q_{OA} is the most dominant factor determining the indoor concentration.

For an AHS where only the Q_{RA} is controlled, and the Q_{OA} is constant, the recommended strategy to reduce the indoor concentration for all discussed conditions A, B, C, and D, is to increase the amount of RA flowrate. This would correspond to reducing the fraction of Q_{OA} in Q_{SA}.

CASE 4

This case represents a VAV system with a constant Q_{RA} (rated value) and varying Q_{OA} flowrates. Different operational conditions were characterised by parameter *R4* defined as $R4=Q_{OA}(actual)/Q_{OA}(rated)$. The values of *R4* and corresponding parameters *R2* and *VR* are listed in Table 2.

The C_{OA} and Q_{OA} were the most dominant parameters affecting the evolution of particle concentrations indoors. For condition A, the trends in evolution of indoor concentration were similar to the trends in evolutions presented in Figure 2a (*CASE 1A*). The concentration started to increase for values *R4*>1.5 (ie. *R1*>0.14), as the filtration system was not capable of sufficiently reducing the concentration of particles in the supplied outdoor air.

For conditions B, C and D the evolution of particle concentration indoors showed a similar pattern to the one presented in Figure 2 d for *CASE 1D.* During approximately the first 30 minutes the indoor concentration decreased more rapidly for larger *R4*, followed by ?? [after this interval the situation reversed WHAT IS MEANT BY REVERSE OF THE SITUATION?]. The steady-state concentrations were higher for larger values of *R4*. Thus, while an increased amount of OA for the first 30 minutes may result in a faster response in reducing particle concentration, prolonging the ventilation under the same operational parameters (larger Q_{OA}) may result in a higher steady-state concentration indoors.

The recommended strategy for condition A is to reduce the amount of OA delivered indoors. For conditions B, C and D it is recommended to increase the OA flowrate, and after the indoor concentration decreased to levels comparable to C_{OA}, return the AHS setting to lower values of Q_{OA}.

THE EFFECT OF FILTRATION

The effect of filtration on indoor concentration has been simulated for a dynamic situation; ie. changing conditions outdoors (Figure 3). In terms of the indoor/outdoor concentration relationship, the dynamic scenario includes the conditions A, B, C and D discussed previously (Table 2). For example during the traffic peak hours 7.00 – 8.00 am, the conditions A ($C_{OA} >> C_o$) occur. The input parameters used in the simulations are presented in Table 1.

The effect of a filter location in an AHS

The effect of a filter installed in different sections of an AHS was investigated. It was assumed that a single filter was located at the outdoor, return, supply or recirculated airstream. The filter locations are presented in Figure 1. The filter efficiency was assumed 30 %, a typical efficiency of filters commonly used in Australia for an office and other work related type of indoor environments.

Figure 3 presents simulated evolution of particle concentration for various scenarios. In general the indoor air concentrations follows the OA concentrations and the highest reduction to approximately 18 % of C_{OA} was achieved by using a supply air filter. Return air filter showed slightly lower reduction, with particle concentration indoors reduced to 26 % of C_{OA}. The indoor concentration has been reduced to 53% and 62% of C_{OA} for simulations with the filter located at OA, and RCL airflow, respectively. This is 2.9 and 3.5 times higher than the concentration achieved by a SA filter.

As can be seen from Figure 3 there appears to be a reduction in indoor particle concentration in comparison with OA particle concentration (about 75% of C_{OA} at the peak level) even for the case with no filters present at all. This is primarily due to a time lag between particle concentartion in indoor air and in outdoor air and to a lesser extent to particle losses due to surface deposition and coagulation. For a sudden change in C_{OA} the indoor concentration changes with certain delay, depending on the response time of the AHS. The response time depends on the operational parameters of the AHS (flowrates) as discussed previously. Particle loss due to surface deposition and coagulation was approximately 7% over the 30-minute interval. This was assessed form comparison of indoor concentration simulated for the particle loss rate set at zero and a value presented in Table 1 {Jamriska and Morawska, 1999c}.[THE MEANING OF THIS IS NOT CLEAR]

It could be concluded that the location of a filter in a building ventilation system is an important parameter in terms of the particle concentration reduction strategies. For a system operating under described conditions, the most efficient reduction was achieved with a filter located at the SA airstream. Slightly smaller reduction effect showed a return air filter.

The effect of a SA filter efficiency

Simulations of the time evolution of particle concentration indoors for a SA filter of efficiencies ε_{SA} in the range from 0 to 90% are presented in Figure 4a. For the same reasons as discussed above, the particle concentration indoors appeared to be reduced even for the condition with no filter ($\varepsilon_{SA}=0$). The comparison of filter effect on particle reduction is based on data related to a peak concentration C_{OA}.

The highest reduction in particle concentration was achieved for a SA filter with 90% efficiency. The particle concentration indoors was reduced to 1.2% of C_{OA} and to 1.6% of the indoor concentration with no SA filter C($\varepsilon_{SA}=0$). This represents a reduction by a factor of 84 and 63 of C_{OA}, respectively.

A SA filter of 15% efficiency, reduced the indoor concentration to 33% of C_{OA} and 44% of C($\varepsilon_{SA}=0$), or by the reduction factors of 3 and 2.3, respectively.

Application of SA filters with 30%, 50% and 70% efficiency, reduced particle concentration to 18%, 9% and 4% of C_{OA}, respectively.

The relation between SA filter efficiency ε_{SA} and particle concentration indoors $C(t)$ is exponential as stems from the Eq 4. Increasing the value of ε_{SA} results in an exponential decrease in $C(t)$. Figure 4b presents the dependency between indoor particle concentration and reduction factors on the SA filter efficiency applied. The reduction factor RF_{OA} was calculated as the ratio between C_{OA} and particle concentration indoors; the reduction factor RF_{In} was calculated as ratio between $C(\varepsilon_{SA}=0)$ and particle concentration indoors $C(\varepsilon_{SA} \neq 0)$.

Figure 4b could be used for an estimation of filter efficiency that needs to be achieved and maintain a pre-defined particle concentration level indoors. For example, to maintain the concentration indoors below 1.0×10^4 particle cm^{-3}, a SA filter with efficiency of about 22% would be required. Similar approach could be followed for an assessment of other parameters required to provide specified conditions indoors.

It could be concluded that the application of SA filter with efficiency between 15% to 90% reduces particle concentration indoors up to ??? and 80 times respectively. The effect of SA filtration is significant with a significant reduction in indoor concentration even for a SA filter of relatively low efficiency of $\varepsilon_{SA} = 15\%$.

The effect of additional filters

The effect of additional OA, RA, and RCL filters on particle concentration indoor was investigated. It was assumed that the AHS was already provided with a SA filter of efficiency $\varepsilon_{SA}=30\%$ and the efficiency of an additional filter varied from 0 to 90%.

Additional outdoor air (OA) filter

The effect of an OA filter on indoor concentration is presented in Figure 5a. An additional filtration of OA reduced indoor concentration, however the effect was less significant in comparison with the reductio due to a SA filter.

Figure 5b shows the dependency between predicted particle concentration; and the reduction factors RF_{OA} and RF_{In} on OA filter efficiency, ε_{OA}. The reduction factor RF_{OA} was calculated as the ratio between C_{OA} and indoor concentration predicted for both filers (ε_{OA}=30%, 0<ε_{OA}<90%). The reduction factor RF_{In} represents the ratio between indoor concentration with only SA filter included (ε_{SA} = 30%, ε_{OA} = 0%) and predicted concentration for both filter included (ε_{OA}=30%, 0<ε_{OA}<90%).

The RF_{OA} was in the range from 6 to 50, the RF_{In} was in the range from 1 (ε_{OA} = 0%) to 9 (ε_{OA} = 90%), respectively. Thus the effect of an additional OA filter could be considered as significant, although to a lesser extent than the effect of SA filter, as discussed previously.

The same decrease of indoor concentration as achieved using a combination of SA filter (ε_{SA} = 30%) and OA filter (ε_{OA} = 90%) could be achieved by using a single SA filter of efficiency of approximately 80%. An additional OA filter of efficiency 30% has the same effect on reduction of indoor concentration as would provide a single SA filter of efficiency ε_{SA} ~40%, ie a SA filter with the efficiency just 10% better than the one considered.

It could be concluded that an additional OA filter further reduced particle concentration indoors up to the factor of nine (RF_{In}) in comparison with the reduction provided only by a SA filter.

The effect of an additional return air filter

An example of evolutions of indoor particle concentration simulated for the condition when an additional return air filter was used is presented in Figure 5a. The dependency between particle concentration and RA filter efficiency ε_{RA} and the corresponding reduction factors are presented in Figure 6. The reduction factors were calculated similarly as above, but for the RA parameters.

Application of an additional RA filter further reduced the indoor concentration from about 6.6×10^3 particle cm^3 ($\varepsilon_{RA} = 0\%$; $\varepsilon_{SA} = 30\%$) to about 2.7×10^3 particle cm^3 for $\varepsilon_{RA} = 90\%$. The reduction factors RF_{OA} were between 5.6 to 13.5 and RF_{In} was in the range from 1 ($\varepsilon_{RA} = 0\%$) to 2.4 ($\varepsilon_{RA} = 90\%$).

For the presented conditions the use of a combination of a SA filter ($\varepsilon_{SA} = 30\%$) and a RA filter ($\varepsilon_{RA} = 90\%$) results in the same particle reduction as the use of a single SA filter of efficiency about 50%. Thus the effect of additional RA filter is less significant than the effect of SA filter and also less significant in comparison with combination of SA and an additional OA filter.

It could be concluded that while an additional RA filter reduces indoor concentration by a factor of up to two, the same reduction could be achieved by using a slightly more efficient SA filter. Thus the use of an additional RA filter as a reduction strategy has little justification.

The effect of an additional recirculated air filter

The effect of an additional RCL filter operated at flowrate of 10% of supply air flowrate was insignificant. The relationship between simulated particle concentration and the RCL filter efficiency and the reduction factors are presented in Figure 7.

The reduction factor RF_{OA} was in the range between 5.6 (ε_{RCL} = 0%) and 6.8 (ε_{RCL} = 90%). For the same efficiency range the RF_{In} was in the range from 1 (ε_{RCL} = 0%) to 1.2 (ε_{RCL} = 90%), or the indoor concentration was reduced approximately by 20% using an additional RCL filter of 90% efficiency. The reduction factors were defined similarly as in the paragraph above.

It could be concluded that the effect of and additional RCL filter on particle reduction indoors for the conditions [OF - say it again] is not significant and the strategy offers only limited application.

THE EFFECT OF THE EFFECTIVE VOLUME OF ENCLOSURE.

The simulation results of the evolution of particle concentration in an enclosure of different effective volume under dynamic conditions are presented in Figure 8. Calculations were conducted for an indoor space of volume between 0.25 to 2.00 of the rated volume (V=3540 m^3) of a hypothetical building with the same input parameters as presented in Table 1.

The predicted concentration displayed an inverse relationship with the enclosure volume, however the variation in concentartion was not significant The calculated concentration increased by up to 4% and decreased by up to 7% for a room of effective volume of 0.25 V and 2.00 V, respectively. The indoor concentration followed the OA concentration with the response time shorter for a room of smaller effective volume (Figure 8).

It could be concluded that the effective volume of the indoor environment does not significantly affect particle concentration indoors.

THE EFFECT OF AIR MIXING FACTOR

Figure 9 presents the effect of mixing factor (k) on the evolution of particle concentartion indoors. The aerosol concentration increases as mixing factor decreases. The ratio of particle concentration predicted for different degree of air mixing $C(k_i)$ and particle concentration predicted for perfect mixing conditions $C(k=1)$ varies between 3.1 ($k=0.3$) and 1.1 ($k=0.9$). For the mixing factors $k=0.7$, and $k=0.9$ the calculated indoor concentrations were 41% and 11% higher than for the perfectly mixed conditions, respectively.

It could be concluded that the mixing factor is an important parameter affecting the particle concentration levels indoors and it should be considered [CONSIDERED IN WHAT SENSE] for the indoor conditions with mixing factor less than approximately 0.7.

CONCLUSIONS

The effect of air filtration, ventilation, air mixing and the enclosure volume on the particle concentration levels indoors have been investigated. Using a simple one zone mathematical model, the topic was studied for several static and dynamic indoor and outdoor conditions representing various scenarios likely to occur in naturally and mechanically ventilated buildings. The evaluation of the effects of the above factors was conducted for a hypothetical building representing an office type of indoor environment with input parameters based on real world data. While the quantitative results of the evaluation are building and conditions specific, using a broad range of input parameters in the presented simulations provided qualitative conclusions that are generally applicable. The following are the main conclusions from the presented study:

- For most indoor environments without strong indoor sources, such as non-industrial work-related environment, the indoor air is dominated by outdoor air.

- In terms of ventilation, the most dominant parameters affecting indoor concentration levels is the amount of OA or its fraction in the SA delivered indoors.

- The time required to achieve steady-state concentration indoors (response time) depends on the operational settings (flowrates) of an AHS and for the usual conditions it is in the range of hours, while the $t_{resp}(0.5C_{\infty})$ could be in the range of minutes. [MEANING AFTER THE COMMA IS NOT CLEAR]
- The steady-state concentration is determined by the C_{OA} and the filtration efficiency of the applied AHS system.

- For the conditions where the concentration outdoors is significantly higher than indoors, an increase in OA flowrate may significantly increase the indoor concentration. The steady state concentration may vary significantly, under usual conditions of up to two orders of magnitude. C_{∞} depends on the C_{OA} and is dominated by the overall removal efficiency of the AHS. [WAS C_{∞} DEFINED? IT WOULD BE BETTER TO AVOID ABBREVIATIONS HERE]

For the cases where a sudden outburst of pollutants appears outdoors it would be recommended to reduce the amount of OA delivered indoors. The process to be efficient requires a continuous monitoring of the pollutant concentration outdoors and a relatively fast response in changing the operational parameters of the ventilation system.

- For the conditions where the concentration outdoors is comparable to the concentration indoors, the concentration indoors is governed by the OA flowrate and the efficiency of the AHS system.

- For the environment with a strong indoor source resulting in a significantly higher concentration indoors compared to outdoors, the most dominant parameters determining the indoor concentration levels is the source strength, Q_{OA} and filtration efficiency of the AHS. The most effective method to reduce the concentration indoors is to operate the AHS at 100% OA mode and increase the SA flowrate to maximum value until the reduced levels indoors are comparable with C_{OA}.

- The air filtration in combination with ventilation reduces the level of particle concentration indoors. The overall effect depends on the filter efficiency, location and the number of filters applied.

- For the usual conditions [WHAT ARE USUAL CONDITIONS?] filtration of the SA provides the most efficient mean to reduce concentration level indoors.

- The application of additional filters could be a suitable strategy for the OA and RA filtration, however, consideration needs to be given to filter location and efficiency to achieve required overall filtration effect.

- The effect of the enclosure volume on particle concentration evolution indoors is insignificant.

- The air mixing is an important factor that may affect the concentration level indoors significantly.

- Although in terms of quantitative assessment the presented results are specific for the conditions considered, the qualitative conclusions made in the study are applicable in general, for most of the real world situations. Assessment of the effect of air filtration, ventilation and other factors on IAQ for specific conditions could be calculated using user defined input parameters. The program is available at www\\xxxxxx.

FIGURE CAPTIONS

FIGURE 1

The schematic diagram of an indoor space equipped with the HVAC system. Denoted are model input parameters.

FIGURE 2

The evolution of indoor particle concentration simulated for static mode (a) Case1A; (b) Case 1B; (c) Case 1C; and (d) Case 1D [MODIFY AS IN HELSINKI PAPER]

FIGURE 3 Dependency between evolution in particle concentration indoors and a filter location (filter efficiency = 30%)

FIGURE 4

Indoor concentration and the reduction factors as a function of Supply Air (SA) air filter efficiency: time evolution; (b) values at time t=9.00 AM

FIGURE 5

Indoor concentration and the reduction factors as a function of Outdoor Air (OA) filter efficiency: time evolution; (b) values at time t=9.00 AM

FIGURE 6

Indoor concentration and the reduction factors as a function of Return Air (RA) filter efficiency. (Values at *t*=9.00 AM)

FIGURE 7

Indoor concentration and the reduction factors as a function of Recirculated Air (RCL) filter efficiency: time evolution (*t* = 9.00 AM)

FIGURE 8

The effect of enclosure effective volume on the evolution in particle concentration indoors

FIGURE 9

The effect of aerosol mixing on the evolution in particle concentration indoors

TABLE CAPTIONS

TABLE 1

Model input parameters used in simulations for a hypothetical office building

TABLE 2

Various input conditions and scenarios for which the static simulations have been conducted.

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