CHARACTERISATION OF FILTER PERFORMANCE IN RELATION TO OUTDOOR AIR QUALITY

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ABSTRACT

Airborne particle size distribution depends on the type of source from which the particles originate - filtration efficiency in turn, is dependent on particle size. Thus, in order to optimise filtration efficiency, it is important to gain knowledge on both: the size distribution of particles in the air to be filtered and the relationship between filtration efficiency and particle size. In addition, assessment needs to be made about the expected concentration level of particles around the building envelope and its time variation. This information is necessary for selecting the most suitable type of filters for the characteristics of particles that dominate in outdoor air.

The aims of this project were to: (i) establish typical scenarios in relation to outdoor air concentration and size distribution, and (ii) to assess filtration performance of tested air filters in ultra fine, submicrometer and $PM_{2.5}$ size ranges.

INDEX TERMS

Air filters, fine particles, $PM_{2.5}$, ultrafine, outdoor air

INTRODUCTION

Filtration efficiency of air filters is usually determined by gravimetric and optical methods which do not provide much information on particles below approximately 0.3 micrometers. The majority of particles in terms of particle number are in the submicrometer and ultra fine (smaller than 0.1 μm) size ranges (Morawska et al. 1998). Recent studies indicate that very small particles may play an important role in air-pollution related health problems. Filtration studies conducted by Hanley et al. 1994 and others demonstrated that filters efficiency is size dependent, varies with filter type and may be a manufacturer specific. Limited information is available on the efficiency of air filters operating in a real environment. Consequently, there is a need to characterise filter performance for the submicrometer and ultra fine size ranges as well as to evaluate filter performance for real-world outdoor air conditions.

The purpose of this paper was to gain information on the efficiency of commercially available filters commonly used in HVAC systems in Australia and North America, and to simulate their effect on IAQ when used for various types of outdoor air conditions. The specific objectives were as follows:

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- Assessment of size dependent and overall filtration efficiency of 30% pleated panel; 65%, 85% and 95% efficiency bag filters tested under different airflow for particles in ultra fine, submicrometer and fine (<2.5 μm) size ranges.
- Characterisation of particle load profile (size distribution and concentration) for outdoor air affected by different types of air pollution sources.
- Simulation of the effect of tested filters on IAQ for different outdoor air conditions.

METHODS

Instrumentation

Filtration efficiency of tested filters was measured in the size range 0.017 – 2.5μm using: (i) a TSI Model 3932 Scanning Mobility Particle Sizer (SMPS), for measurements of the size distribution and concentration of particles in the size range from 0.017 to 0.643 μm, and (ii) TSI Model 3394 Aerodynamic Particle Sizer (APS) for particles in the size range from 0.643 to 2.5μm. The time resolution for SMPS and APS was set at 120 and 20 seconds, respectively. Both instruments were calibrated prior to the measurement using latex spheres.

Tested filters

- *30% efficiency pleated panel filters*: Nonwoven cotton/synthetic blend media rated at 25-30% efficiency and 90-92% arrestance on ASHRAE Standard 52.1-92

- *65%; 85%; 95% efficiency –bag filters:* Synthetic media, electrostatically charged microfiber graded mat, with a light spun bonded top sheet and a heavy-weight spun bonded support scrim. The filters have an average efficiency of 60-65% (80-85%; 90-95%) and average arrestance of no less than 97.5% (99%; 99.5%) on ASHRAE 52.1-92.

Testing system

The measurements were performed at a test rig designed according to Australian AS1324.2 - 1996 Standard, which is based on the ANSI/ASHRAE 52.1-1992 Standard. The test rig operated at positive pressure with a driving fan at the downstream end of the rig, forcing HEPA filtered air into the duct system. Filters were tested with NaCl test aerosols generated by a Collison nebuliser from 30% (by weight) aqueous solution. Air was sampled from two identical sampling lines (upstream and downstream), each consisting of an L-shaped sampling probe designed for isokinetic sampling, and a three-meter long conductive plastic tube connected the SMPS, APS inlet and the sampling probe outlets.

Test methodology and filter efficiency calculations

The testing methodology was based on the ASHRAE 52.2-1999 Standard. Particle number concentration of challenge aerosols was measured upstream and downstream of tested filters in defined size ranges. The measuring sequence for sampling and purging upstream and downstream, as well as the methodology for assessment of the parameters affecting measured upstream and downstream concentration, such as the correction factor for test rig, air temperature and relative humidity were also conducted according to the standard. The performance of the filters was assessed at 100%, 70% and 40% of Q_{rated} airflow ($Q_{rated} = 0.944$ $m^3 s^{-1}$). The filter efficiencies and associated errors were calculated according to formulas presented in the ASHRAE Standard 52.2-1999. The efficiency for $PM_{2.5}$ was calculated from the volume concentration and size distribution, which was recalculated from particle number characteristics. Particles sphericity and unit density were assumed for mass calculations.

Ambient air characteristics

Several ambient air load profiles (particle size distribution and concentration) representing different outdoor air conditions encountered in Brisbane, Australia, were considered for the study of I/O relationship: (i) typical well mixed urban outdoor air; (ii) diesel vehicle emissions dominated ambient air; (iii) ambient air dominated by brick cutting; (iv) ambient air dominated by coal crushing. The ambient air data were obtained from previously conducted studies by the authors (Morawska et al. 1998; and unpublished data).

Simulation method

The predicted particle concentration and size distribution of supply air can be calculated from known outdoor air concentration and/or size distribution and air filter efficiency. Supply air concentration values were calculated as a product of outdoor particle concentration and average filter penetration values for particles of each size category. Filter efficiency obtained from filter testing with NaCl at 100% of Q_{rated} was used for calculations. For each ambient air condition it was assumed that filters operated at 100% of rated airflow with a single pass of the ambient air through the filter (no return air).

RESULTS

Fractional and average filter efficiency

Fractional and average efficiencies of tested filters are presented in Figure 1 and Table 1 respectively. The following conclusions could be made in relation to the obtained results:

- The lowest fractional efficiencies for bag filters are for particles in the size range of about 0.2 μm, while the highest for particles in the size ranges below 0.050 μm and above 2 μm.
- The filtration efficiencies of bag 95% and bag 85% filters measured at 100% of rated flowrate were comparable, with the average efficiency of 59-65%, and 49-58%, respectively.
- The bag 65% filters were less efficient with the average efficiency for ultrafine, submicrometer, and $PM_{2.5}$ particles in the range between 17% to 29%, and the minimum fractional efficiency approximately 10% to 20%.
- The efficiency of pleated filters below 0.5 μm was almost negligible (less than 4%) and increased to approximately 40% for particles larger then 2 μm.

Table 1. Average efficiency for tested filters in particle size ranges: a) **U**-Ultra fine particles; b) **S**-Submicrometer, and; c) $PM_{2.5}$.

FILTER TYPE	**AIR- FLOW in % of Q_{rated}[1)]**								
	100%			**70%**			**40%**		
	U	**S**	**$PM_{2.5}$**	**U**	**S**	**$PM_{2.5}$**	**U**	**S**	**$PM_{2.5}$**
BAG 95%	**0.647**	**0.592**	**0.648**	**0.713**	**0.634**	**0.687**	**0.810**	**0.785**	**0.811**
BAG 85%	**0.546**	**0.494**	**0.584**	**0.624**	**0.547**	**0.605**	**0.770**	**0.733**	**0.763**
BAG 65%	**0.230**	**0.171**	**0.285**	**0.334**	**0.240**	**0.299**	**0.628**	**0.558**	**0.574**
PLEATED[2)]	**0.035**	**0.029**	**0.092**	**0.040**	**0.036**	**0.046**	**0.428**	**0.416**	**0.425**

[1)] Q_{rated}= 0.944 $m^3 s^{-1}$; [2)] The results are associated with a large level of uncertainty (STD comparable with average values) except for data measured at 40% of Q_{rated}.

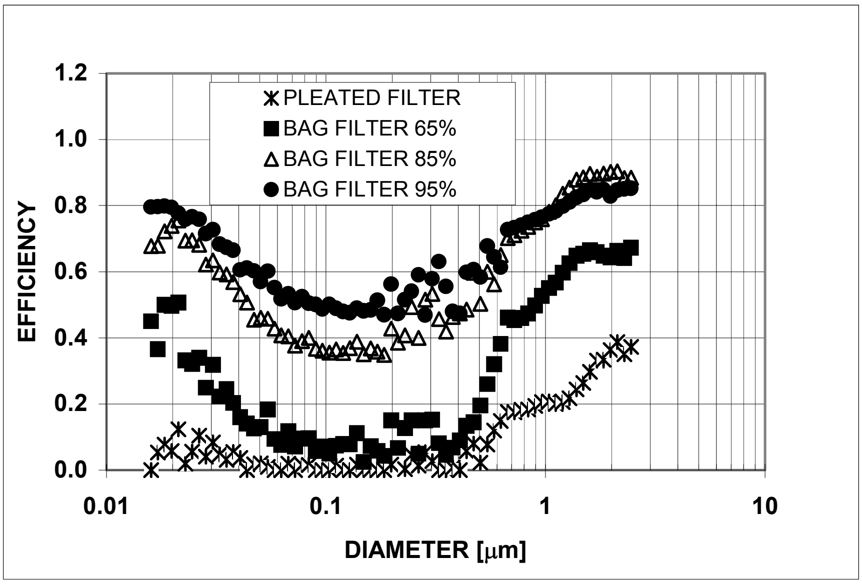

Figure 1. Fractional efficiency for tested filters challenged with NaCl aerosol at 100% rated flowrate.

Outdoor ambient air conditions

The total number and mass concentrations of particles of different size categories encountered in different environments in Brisbane are presented in Table 2.

In terms of particle number, ultra fine particles (< 0.1 µm) contributed between 80-85% to the total number concentration of fine particles (<2.5 µm). This is in comparison with contributions of 1% to 8% contribution to particle mass. Almost 100% of fine particle numbers were smaller than one micrometer. For particle mass the contribution of submicrometer particles to $PM_{2.5}$ represent 63%, 95%, 90% and 37%, for the urban, diesel emissions, brick cutting and coal crushing dominated air, respectively. The $PM_{2.5}$ concentration is relatively high and comparable with values set by the $PM_{2.5}$ NAAQS US EPA Standard.

Table 2. Particle number and mass concentration of different types of outdoor air

	PARTICLE SIZE RANGE	**URBAN AIR**	**DIESEL EMISSIONS**	**BRICK CUTTING**	**COAL CRUSHING**
NUMBER Concentration (particle cm^{-3})	**ULTRA FINE**	6.83E+03	3.45E+04	3.03E+04	6.49E+03
	SUBMICROMETER	8.00E+03	4.32E+04	3.44E+04	7.69E+03
	FINE (<2.5 µm)	8.00E+03	4.32E+04	3.44E+04	7.69E+03
MASS Concentration (µg m^{-3})	**ULTRA FINE**	0.5	2.0	2.1	0.3
	SUBMICROMETER	8.4	60.8	24.2	9.5
	$PM_{2.5}$	13.4	64.4	27.0	25.5

Relationship between supply and outdoor air particle concentrations for the investigated filters

Using experimentally derived filter performance characteristics, supply air versus outdoor concentrations for submicrometer particles and $PM_{2.5}$ particles were calculated for the case of a single pass of ambient air through a filter (no return air) at 100% rated air flow. The results are presented in Figures 3 and 4.

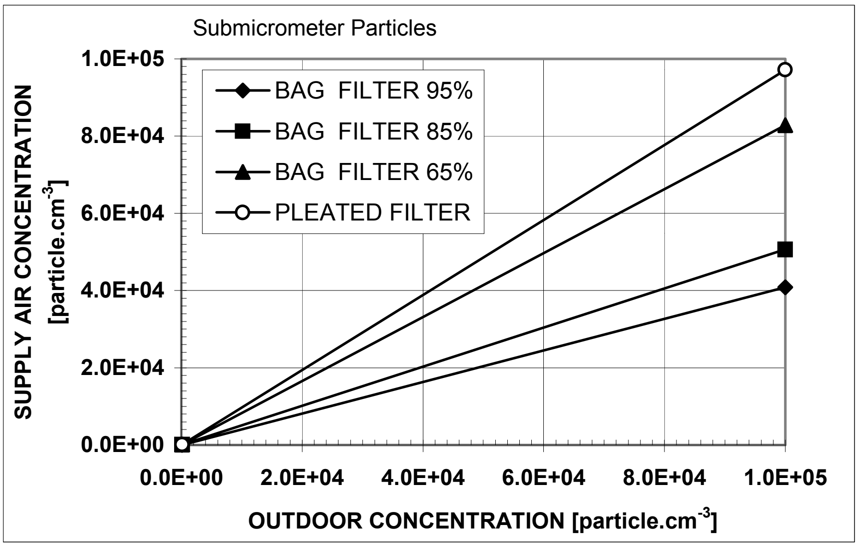

Figure 3. Supply air versus outdoor air particle number concentration for the submicrometer size range.

The set of linear relationships presented in these figures can be used to determine the type of filter(s) that could be used to achieve target supply air concentration levels for specific cases of outdoor concentration levels. If, for example, outdoor concentration of submicrometer particles was of the order of $3x10^4$ particles cm^{-3} (a concentration level commonly encountered in the vicinity of a moderately busy road), and the target supply air concentration was $2x10^4$ particles cm^{-3}, bag 85% and 95% filters would be able to reduce the concentration below the target level, while bag 65% and pleated filters would not (see Figure 3).

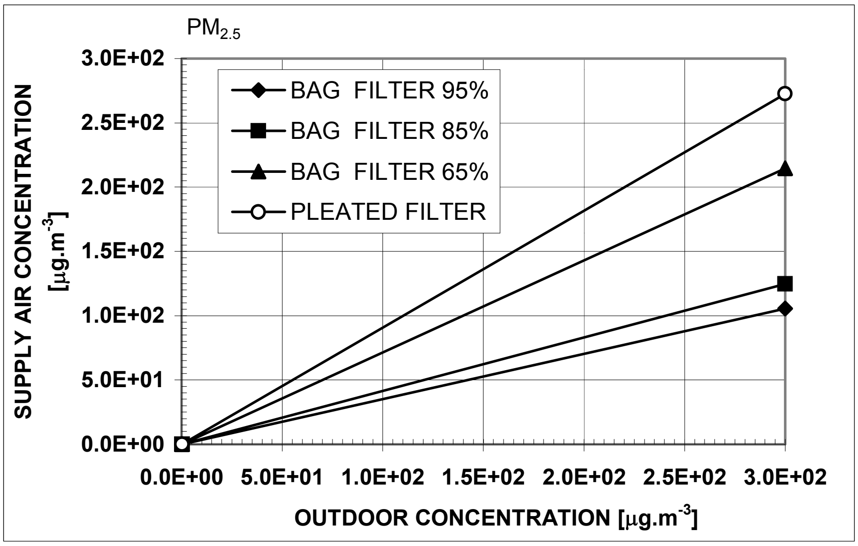

Figure 4. Supply air versus outdoor air $PM_{2.5}$ concentration

While there are no standards or even guidelines yet for number concentration levels of ultra fine or submicrometer particles, the US EPA NAAQS Standard specifies an annual $PM_{2.5}$ concentration limit of 15 µg m^{-3} and 24-hour average at 65 µg m^{-3} (98th percentile). Figure 4 can be used to assess, which filters could be applied to achieve these concentration levels of supply air for specific outdoor concentration levels. This type of assessment is somewhat simplistic because it does not take into consideration that outdoor concentration levels vary due to the variation in the source strength (for example traffic density changes on the nearby road) and meteorological conditions (most importantly wind speed and wind direction). A more advanced approach would be to model exposure of the occupants of the building taking into consideration all of the above factors, and to base the choice of filter on the exposure, rather than on concentration levels. This approach in many cases may not be possible, if there are no sufficient data for comprehensive exposure assessment. Also, in case return air was used, additional calculations would be required to take into account the fraction of outdoor air in the supply air, and multiple passes of air through the filter. Despite these limitations, the presented graphs can be used as a tool for assessment where basic information about outdoor concentration levels is available, and target supply air concentration levels are set.

CONCLUSIONS

Based on the particle counting technique, fractional and average filtration efficiency of four commercially available air filters commonly used in HVAC system was experimentally determined for particles in ultra fine, submicrometer and $PM_{2.5}$ size ranges. Performance of tested filters was assessed for several outdoor air conditions and a simple method was developed to assess the I/O relationship. The method and data provided can be used by building architects, planners and other professionals for better design and assessment of HVAC systems used in various types of outdoor conditions.

ACKNOWLEDGMENT

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