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The building envelope as an air filter

B. J. Taylor[a,*], R. Webster[a], M. S. Imbabi[b]

[a] The Scott Sutherland School of Architecture, The Robert Gordon University, Aberdeen, AB10 7QB, U.K.
[b] The Department of Engineering, Kings College, The University of Aberdeen, Aberdeen, AB24 3UE, U.K.

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Abstract

Recent research suggests that fine-particulate air pollution increases the incidence of lung disease and premature death. In this paper, single fibre filter theory was used to predict the theoretical particulate collection efficiency of air permeable walls (dynamic insulation). The relationship between particle diameter and filtration efficiency for dynamic insulation, as a function of flow rate, is examined and compared to that for a conventional filter. Factors such as filter penetration as a function of flow rate, filter thickness, and packing density for a range of particle diameters are also presented. The findings suggest that, in addition to reducing heat loss through the building fabric, dynamic insulation can act as a high performance air filter in naturally ventilated buildings, thus providing a viable and attractive alternative to mechanical air-conditioning in congested urban environments.

1. Introduction

In many of today's cities there are sites so polluted by noise and poor air quality that they cannot be developed unless air-conditioning is installed. Furthermore, urban sites needing a deep plan building will also require air-conditioning if the maximum occupation density is to be achieved. Other claimed benefits of air-conditioning are that it provides a degree of protection against developments on neighbouring sites which may disrupt the air flow of a naturally ventilated building and that it provides some flexibility in meeting changes in occupation density and in partitioning buildings.

These advantages are bought at a high price. In large urban buildings such as commercial offices in city centres the major energy costs are for air-conditioning, followed by computer suites and lighting. Furthermore, it is estimated that at least 30% of the construction cost of a large air conditioned office is in the mechanical services.

The size and cost of air-conditioning plant can be reduced by drawing into the building only that amount of fresh air required for human comfort and reducing the solar gain (the major source of heat in summer) by judicious use of glazing and external shading. Further reductions in air-conditioning plants can be achieved by making use of thermal mass, night ventilation, chilled ceilings, and stack effect. Naturally ventilated buildings may still require ducting, heat exchangers and air filters, but these need to have low pressure losses.

Dynamic insulation (also known as pore ventilation), in which cool fresh air is drawn into the building through air permeable walls, has been viewed exclusively as a means of reducing the conduction heat loss through the building envelope. This form of construction not only reduces the amount of ducting and the size of ancillary mechanical plant, but also, as this paper will demonstrate, has the potential to act as a highly efficient particulate filter. Dynamic insulation will be described briefly for those not familiar with this technology. Then it will be shown how the building envelope itself can be used to provide good quality air, even in the midst of heavily polluted external environments, with low pressure loss, thus facilitating the design of naturally ventilated buildings. The anticipated outcome is that heavily polluted city centre sites could be developed at considerably lower capital and operational cost by using dynamic insulation to facilitate natural ventilation.

2. Dynamic insulation

A dynamically insulated envelope, which permits the movement of air, moisture, etc., through the external walls of a building, is constructed using air permeable materials. Air flows through the wall, driven by a difference in pressure between inside and out, created by fans

* Corresponding author. Tel.: 0044 01224 263500; fax: 0044 01224 263535.

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or stack effect. In essence, air flowing in through the wall picks up the heat that is being conducted outwards. The heat lost to the outside can be reduced to practically zero by quite small air flows. A typical wall construction for a house is shown in Fig. 1. Taylor, et al. [1] describe in detail the heat and mass transfer processes occurring in air permeable walls, showing how the U-value for a multilayered wall can be calculated knowing the total thermal resistance and the air flow rate. An inward air flow also eliminates interstitial condensation because the humidity of the air decreases as it warms up going through the wall.

3. Health considerations

Before going on to consider the filtration characteristics of the above dynamically insulated envelope, it is necessary to establish the current state of knowledge of the effect of particulate pollution on human health. Recent research in the U.S. suggests that fine-particulate air pollution (diameter less than 2.5 μm) increases the rate of mortality [2]. Seaton et al. [3] suggest that it is the large numbers of ultrafine particles (less than 0.1 μm in diameter) particles present in today's atmosphere rather than the inhaled mass of particles, which consists of a much fewer number of large (10 μm in diameter), that is responsible for increasing mortality and emergency-room visits for asthma when there are episodes of increased particulate pollution. Studies on rats have shown that particles which are non toxic in the micron size range can be toxic at sub-micron sizes. The ultrafine particles are able to penetrate and settle in the lung aveoli and the acidic nature of these particles inhibits the body's defences and results in alveolar inflammation. Not only do the particulates themselves irritate the lungs, but they also have adsorbed on their surfaces chemical air pollutants which can damage sensitive tissue. The main source of particulate pollution in urban areas is exhaust emissions from road transport [4]. Because fine particles have a high residence time in the atmosphere and hence can travel further, exhaust emissions are also thought to be the cause of the rise in fine particulate pollution in the countryside.

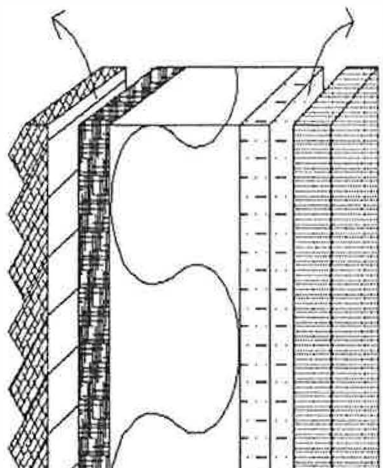

Fig. 1. Breathing wall construction schematic.

4. Application to an office block

The first step in considering the filtration characteristics of the building envelope is to determine the airflow through the wall. Since, in this paper, we are merely attempting to demonstrate the feasibility of the building envelope acting as an air filter, and to outline the design approach, it is sufficient to estimate the order of magnitude of the air speed through the wall. However, in designing a practical building envelope that includes air filtration as one of its roles, more detailed calculations would be carried out to take account of the variation over the building envelope of the pressure differences due to the external and internal air flows and temperature differences.

For simplicity, we take, as an example, a cuboidal office block of length, L, breadth, b, height, h, Assuming the height between floors to be 3.6 m, the number of floors in the building, n_f, is easily calculated. Those parts of the walls which are not glazed will be assumed to be air permeable. The percentage of the walls that are glazed is denoted by g. The space allocation per person, n_p, is 1 person/1 0 m^2. We shall assume that fresh air is provided only for the removal of CO_2, odours, etc. and that cooling requirements are met by other means such as those listed in the Introduction. Assuming that there will be some smokers in the building, the fresh air requirement per person [5], q_f, is 16 l/s. This is equivalent to 1.6 ach. It is very easy to show that the required air flow, V (m/s), through the permeable wall area is

$$V = \frac{0.01 n_p q_f L}{7.2\left(\frac{L}{b}+1\right)(100-g)}$$

Some very interesting conclusions for the required air flow can be drawn from this formula:

(1) *Air flow through the wall is independent of the height of the building*. This is because as the height increases, the increasing wall area which is admitting air is cancelled directly by the increasing number of occupants.
(2) *The air flow increases as the scale, length, L, of the building increases*. The bigger the building, the greater the floor area, and the more people there are.
(3) *The air flow decreases as the aspect ratio of the plan (L/b) increases*. The air flow is a maximum for a square floor plan (maximum number of occupants) and decreases as the building gets long and narrow.

For a building with plan area 30 m × 30 m and 50% glazing, the air flow required through the permeable wall is 24 m^3/m^2h or 0.007 m/s, irrespective of the height of the building. The above estimate thus represents an average over the whole building of the air required through the envelope. In practice, the air flow will vary over the building envelope and with time. However, since the magnitude of this flow is two order of magnitudes lower than that used in conventional air-conditioning filters, this variation will not invalidate our conclusions regarding the filtration efficiency of the envelope.

With this information, the permeable wall can now be designed. In order to draw this amount of air through the wall with only a 5 Pa pressure difference (a 10 C temperature difference for a building height of 10 m provides a stack pressure of 4.3 Pa) then the permeance of the wall needs to be 4.8 m^3/m^2hPa or higher. Table 1 provides results of air permeability measurements for some building materials that could be used in dynamic insulation [6, 7].

The required permeance of the wall can be achieved in several ways: 60 mm of glass fibre or cellulose, or 13 mm of mineral wool. Both the cellulose and glass fibre provide an adequate depth for filtration and minimum heat loss. At an air flow of 24 m^3/m^2h, the heat loss through the insulation is effectively zero and the heat loss through the envelope is determined almost entirely by cold bridging through the structure. At lower air flows through the wall the U-value can be readily calculated [1], to which cold bridging effects may be added if appropriate. Mineral wool could be used if the insulation batts were made more air permeable. Dynamic insulation offers the potential of reducing the weight and cost of mineral wool insulation. More generally, dynamic insulation can achieve any required U-value with thinner construction than conventional walls [6].

5. Air filtration

An air filter for an air-conditioning system has an open fibrous structure. The fibres are relatively far apart from each other (100 μm) compared with their diameter (10 μm). This means that fibrous air filters have a porosity in the region of 90–95%. The mechanisms (excluding electrostatic and atomic forces) by which particles are trapped by a filter are (Fig. 2):

(a) *Direct interception*, which involves a particle following a streamline and being captured if it comes into contact with a fibre.
(b) *Inertial impaction*, in which a particle is captured because it deviates by its own inertia from the streamlines around the fibre.
(c) *Diffusional deposition*, in which Brownian motion of the particle brings it into contact with the fibre.

The high porosity of air filters means that particle straining or sieving, in which a particle is held between two or more adjacent fibres, seldom happens. The behaviour of air filters can be described to a good approximation by single fibre theory [8]. Single fibre theory calculates the flow fields around a fibre, taking into account the effects of neighbouring fibres. These flow fields are then used to calculate, for each of the above mechanisms, the trajectories of particles being carried along by the air. The total number of particles captured is assumed to be the sum of particles captured by each mechanism with

Table 1
Measured air permeability of building materials

Material	Permeability (m^2/hPa)	Component	Permeance (m^3/m^2hPa)	Pressure drop (Pa)[1]
Plasterboard	1.06×10^{-5}	12 mm sheet	8.81×10^{-4}	1140
Thermal block (density 850 kg/m^3)	1.6×10^{-5}	100 mm block	1.9×10^{-4}	526
Fibreboard	1.34×10^{-3}	12 mm sheet	1.16×10^{-1}	8.6
Pumalite (density 870 kg/m^3)	0.036	100 mm block	3.6×10^{-1}	2.8
Mineral wool[2] (density unspecified)	0.066	14 mm	4.8	0.2
Cellulose/wet blown (density 47 kg/m^3)	0.283	60 mm	4.8	0.2
Glass fibre[2] (density 20 kg/m^3)	0.285	60 mm	4.8	0.2
Sheep's wool (density 28 kg/m^3)	1.8	140 mm	13.0	0.08

[1] Pressure drop calculated at flow rate of 1 m^3/m^2h.
[2] Derived from Ref. [4].

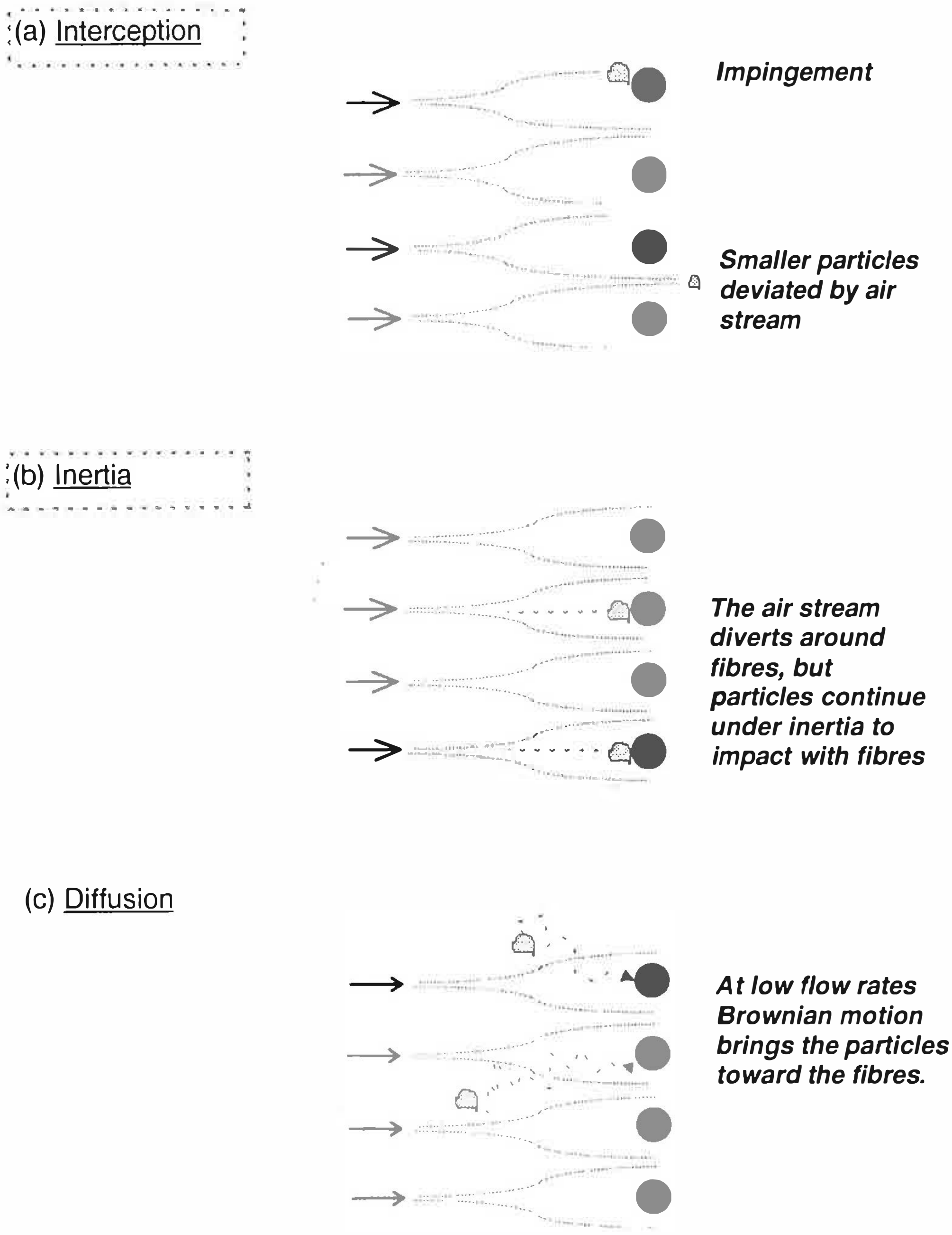

Fig. 2. Particle capture mechanisms.

corrections for interaction effects. The theory enables the effects of particle and fibre sizes, porosity and particle density on single fibre collection efficiency to be calculated.

Figure 3, in which the single fibre particle capture efficiency is plotted as a function of particle size for two air velocities, illustrates the results of such calculations. The insulation is assumed to have a mean fibre size of 10 μm and a packing density of 0.1. The higher air velocity (0.8 m/s) is typical of that in an air-conditioning air filter, whereas the lower one (0.007 m/s) is that calculated above for a 30 m $\times$ 30 m office block. A fibre diameter of 10 μm is typical of glass fibre which may be used in either dynamic insulation or a conventional filter. It can be clearly seen that the very low air velocities in dynamic insulation results in very much improved collection efficiencies for particles less than 1 μm in diameter. Note that a single fibre capture efficiency greater than one, implies that particles initially at a distance greater than the fibre radius perpendicular to the main flow direction are captured. At the low air flows in dynamic insulation, diffusional deposition becomes extremely efficient for sub-micron

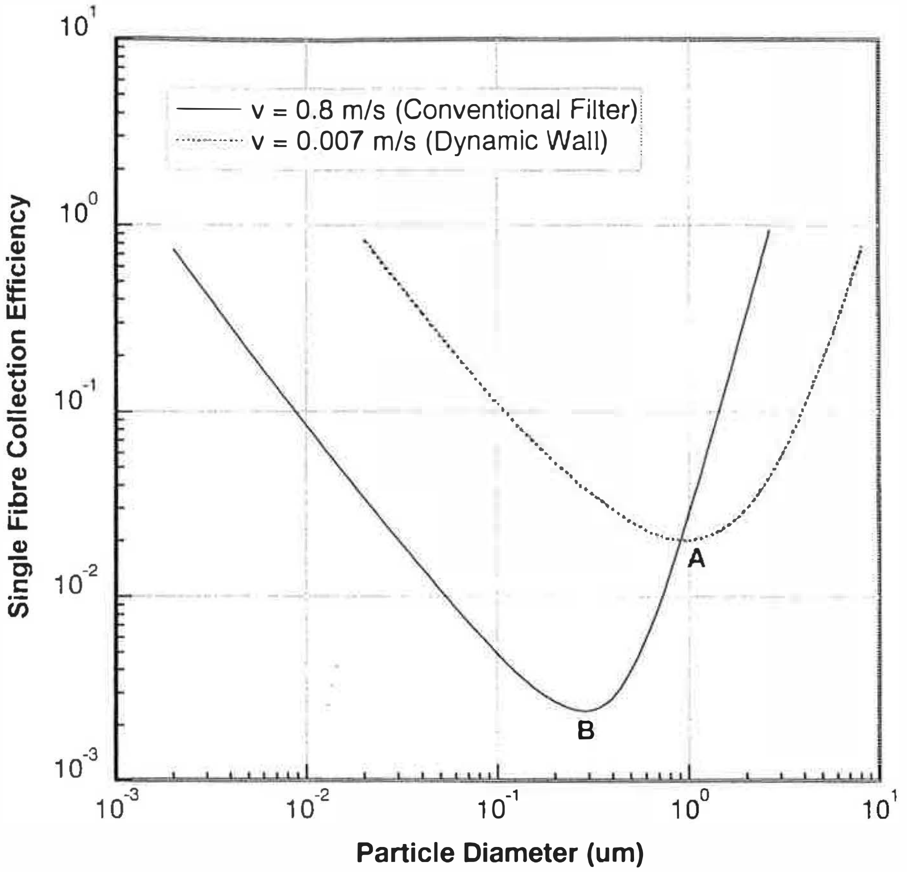

Fig. 3. Effect of air speed on single fibre collection efficiency. Points A and B indicate the size of particle least easily captured by a single fibre at low air flow and high air flow respectively.

particles. The most penetrating particle size is about 1 μm for dynamic insulation, (Fig. 3, point A), compared, with 0.3 μm, (point B) in a conventional filter.

A real filter consists of many fibres at varying orientations to each other. However, the efficiency of a filter as a whole depends on the single fibre efficiency and the thickness of the filter. Each successive layer of fibres captures the same proportion of particles from the air stream. As a consequence, although the single fibre efficiency for a given particle size might be quite low, if the filter is sufficiently thick, its overall performance can be very good for that particle size. Filter efficiency is often described as percentage penetration. The penetration, for particles of a given size, is simply the concentration of particles leaving the filter divided by the concentration of particles entering the filter. The penetration also depends on how tightly the fibres are packed together and the radius of the fibre.

The particle penetration for a filter of thickness 20 mm is shown in Fig. 4 for the corresponding single fibre collection efficiencies shown in Fig. 3. It shows again that dynamic insulation can effectively prevent the ingress of small air borne particles into a building. Its relatively poor performance at the larger particle sizes, due to the relatively weak inertia capture mechanism, is not a handicap, since in practice, as demonstrated above, dynamic insulation would be at least 60 mm thick. At this thickness of filter media, particle penetration will be effectively zero for all particle sizes. Thus dynamic insulation has the potential performance of a high efficiency particulate air (HEPA) filter.

It should be stressed that dynamic insulation achieves this remarkable filtration performance because the air flows are very much lower than in conventional HEPA filters.

6. Filter clogging

It can be seen from Fig. 5 that only 1 mm of dynamic insulation provides a formidable barrier (less than 1% penetration) to airborne particles less than 0.022 μm in diameter and greater than 7.5 μm in diameter. Thus particles greater than 10 μm in diameter are effectively trapped on the surface of the filter. This suggests the possibility that the spaces between the filter fibres at the surface would eventually become blocked and that, in effect, a filter cake would form on the surface. The filtering medium would then become the filter cake rather than the insulation. Filter cake would have a much lower

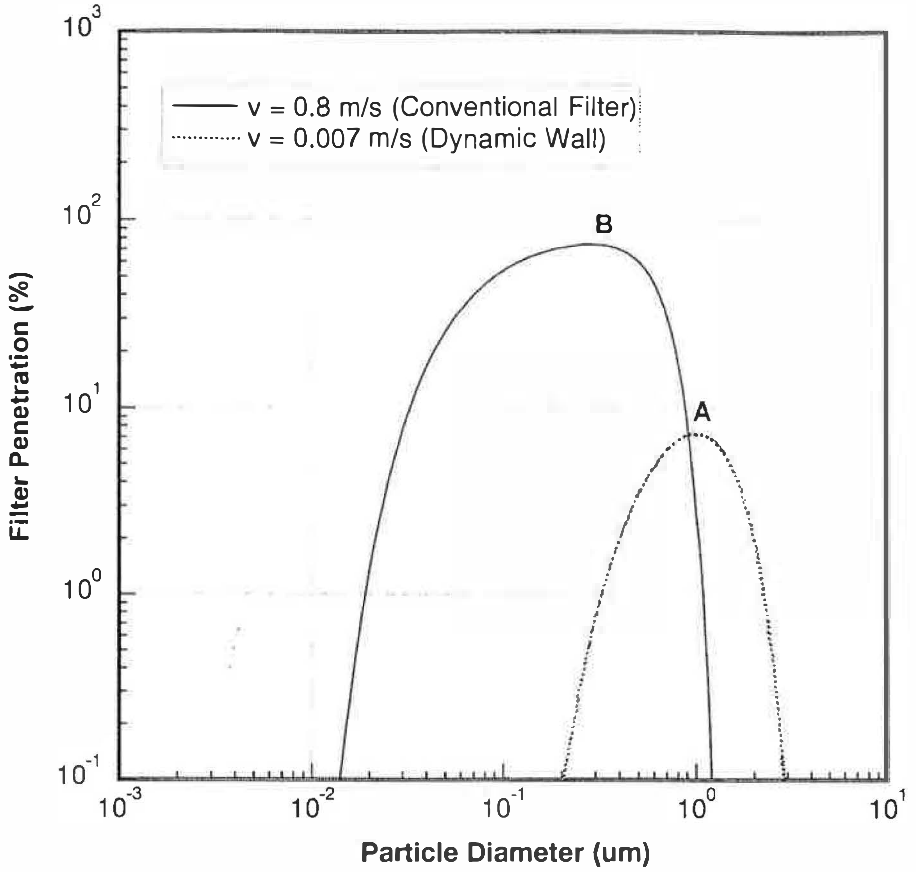

Fig. 4. Effect of air speed on filter penetration. Points A and B indicate the size of particle that most easily penetrates a 20 mm filter at low and high air flows, respectively.

porosity than the filter medium and hence have a much higher pressure drop across it, compared with insulation of the same thickness at the same air flow rate. This change in the pressure drop characteristic with increasing dust loading (Fig. 6) defines the point at which filter clogging begins. It marks the transition from depth filtration to surface or filter cake filtration.

Studies of porous ceilings in barns where the ventilation rate can be as high as 80 m^3/m^2h have shown that on samples that had been installed for 6–16 years there was no noticeable decrease in air permeability compared with the values when installed. The pressure increase (from 20–25 Pa) due to dust accumulating in mineral wool insulation is insignificant for a barn [9]. This may be due to:

(1) the relatively low density (15 kg/m^3) and hence high porosity of the insulation.
(2) the relatively high pressure drop across the ceiling (20–30 Pa) that can be tolerated in a barn may mask the small change in pressure difference that may not be acceptable in other building types.
(3) the average dust concentration 50 $\mu g/m^3$ in the Swedish countryside may not have been sufficiently high to induce filter cake formation in the insulation even at the high flow rates.
(4) the delicate filter cake may have been disturbed during the process of taking samples of insulation and during the subsequent air permeability measurements.

Sallvik [9] estimates that the life time of a porous ceiling using mineral wool and an average flow rate of 80 m^3/m^2h would exceed 20 years. In homes and commercial buildings, the ventilation rate will be an order of magnitude smaller and the rate of dust accumulation in the walls will be correspondingly slower.

7. Noise pollution

A fibre packing density of 0.1 means that the insulation has a fairly open structure and so its sound insulation characteristics may not be adequate for noisy city centre sites. However, using insulation with a higher packing density, say 0.2, would not only improve the sound insulation but also considerably improve the filtration characteristics. Figure 7 shows that doubling the packing density reduces the particle penetration through the wall by a factor of 100. An adverse consequence of doubling the packing density is that it would also increase the pressure drop across the wall by 2–4 times. In the

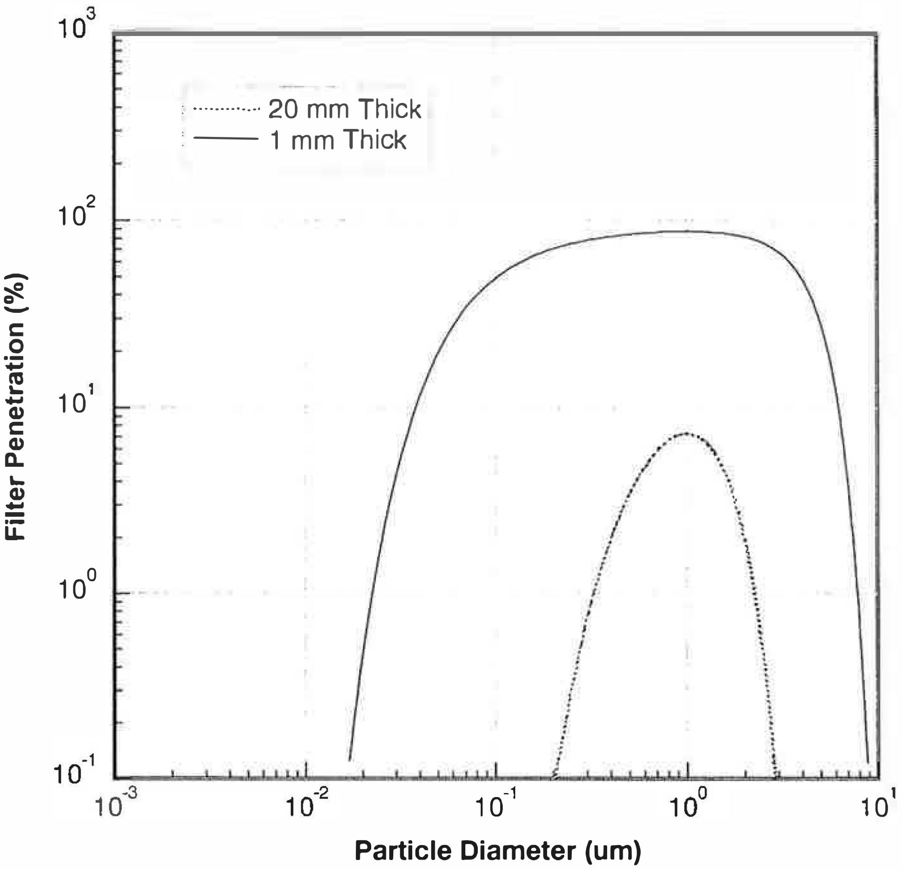

Fig. 5. Effect of filter thickness on filter penetration. In a dynamic wall, particles less than 0.01 μm and greater than 10 μm in diameter are effectively all trapped on the surface of the insulation (surface filtration). Particles in the intermediate size range are trapped within the insulation (depth filtration).

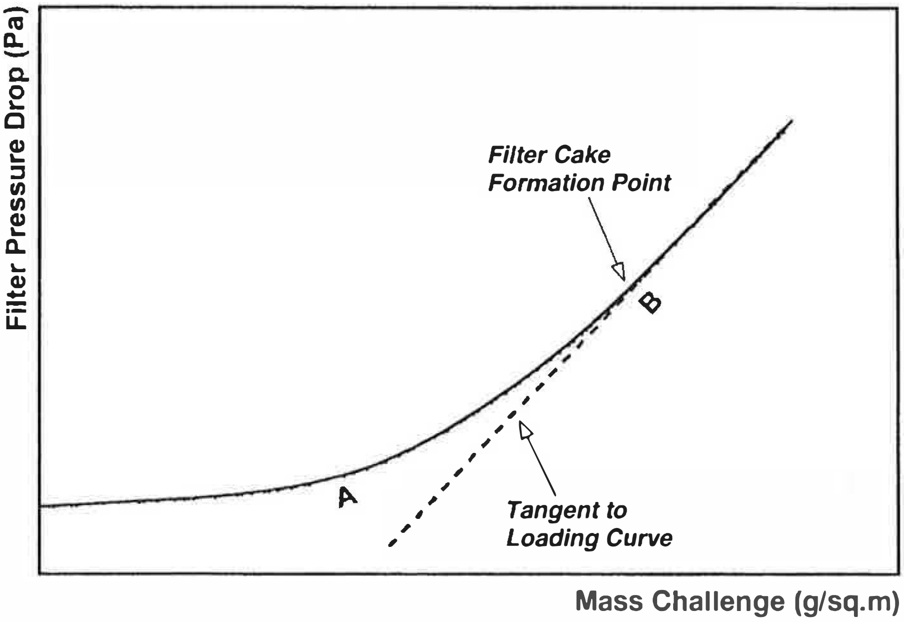

Fig. 6. Pressure drop vs mass challenge per filter face area. Mass Challenge = amount of dust accumulating per square meter of filter area. Between A and B dust is accumulating on the surface of the insultation, increasing the pressure drop. At point B the filter cake becomes the filter medium, rather than the insulation.

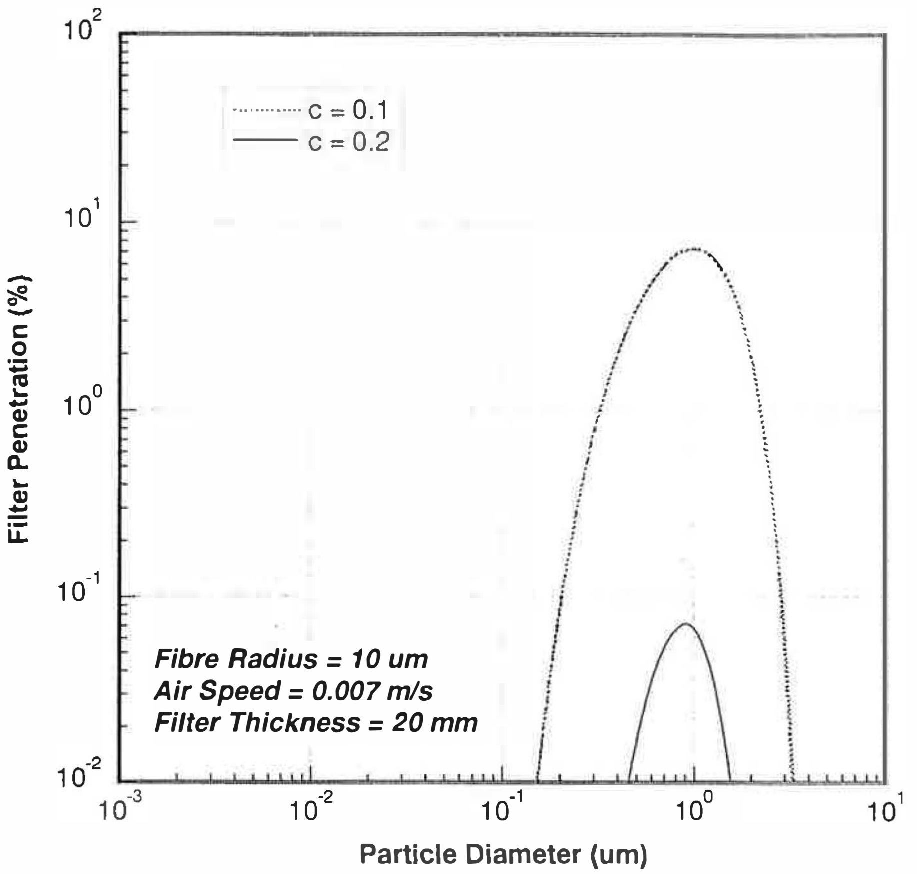

Fig. 7. Effect of packing density on filter penetration. Doubling the density of insulation in order to increase its sound attenuating properties also increases the filtration effectiveness by a factor of 100.

development of an air permeable wall capable of filtering air, there may have to be some compromises between good filtration and sound insulation characteristics and low pressure drop.

8. Conclusions

Dynamic insulation with its inherently very large face area and hence very low face velocities, is extremely efficient at capturing particles less than 0.5 μm in diameter. It will also stop particles larger than 5 μm in diameter. Furthermore the thickness of insulation that would be used (60 mm or greater) means that particles in the lung damaging size range, 0.5–5 μm, are effectively trapped within the depth of the insulation, despite the lower single fibre collection efficiency for this size range. The net effect is that dynamic insulation could potentially approach the performance of HEPA filters with a considerably lower pressure drop, thus making dynamically insulated walls the ideal choice for naturally ventilated buildings.

Research is needed to measure the particle penetration of air permeable building materials at the low air velocities used in dynamic insulation and to investigate the formation of filter cake on these materials. Filter cake is in itself a very effective filter medium, but at the expense of a higher pressure loss. The sound insulation characteristics of these thermal insulation and filtering media also need to be determined.

The potential benefit is that city centre sites, heavily polluted by particulates and noise, could be developed at considerably lower capital and operational cost by the use of natural ventilation drawing air through air permeable walls.

Acknowledgements

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