FILTRATION OF PARTICULATE AIR POLLUTION USING DYNAMIC INSULATED BUILDING ENVELOPES

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ABSTRACT: *Recent research suggests that fine-particulate air pollution increases the incidence of lung disease and pre-mature death. Single fibre filter theory is 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 is 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 polluted urban environments.*

KEYWORDS

Air, filtration, particulate, building, wall, dynamic insulation, pore ventilation, health, clogging, ventilation

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. 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 for 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. Solar gain, the major source of heat in summer, can be controlled by use of glazing and external shading.

Dynamic insulation (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. It will be shown that 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 to facilitate the design of naturally ventilated buildings. The anticipated outcome is that heavily polluted city centre sites could be developed at 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 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 zero by quite small airflows. Taylor, Cawthorne and Imbabi (1996) 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 airflow also eliminates interstitial condensation because the humidity of the air decreases as it warms up going through the wall.

3. HEALTH CONSIDERATIONS

Recent research in the US suggests that fine-particulate air pollution (diameter less than 2.5 mm) increases the rate of mortality (Dockery, 1993). Seaton *et al* (1995) suggest that it is the large numbers of ultrafine (less than 0.1 µm in diameter) particles present in today's atmosphere, rather than the inhaled mass of particles, that is responsible for increasing mortality and emergency-room visits for asthma when there are episodes of increased particulate pollution. The main source of particulate pollution in urban areas is exhaust emissions from road transport (QUARG, 1996).

Fresh air is not just the absence of particultes. Urban outdoor air also has higher concetrations of CO_2, NO_x and volatile organic compounds (VOC) mainly produced by motor vehicles. The VOC's could be adsorbed by activated charcoal incorporated into the dynamic insulation. However, this paper will focus on particulate removal.

4. 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 porosity in the region of 90%. The mechanisms (excluding electrostatic and atomic forces) by which particles are trapped by a filter are:

(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 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 (Davies, 1973). 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 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 1, 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 assigned 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. The lower velocity (0.007 m/s) is that calculated for a 30m X 30m plan office block with an occupancy of 1 person/10m^2 and fresh air supplied at the rate of 16 /s/person (Taylor, Webster and Imbabi, 1998).

A 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 greatly improved collection efficiencies for particles less than 1 µm in diameter. At low air flows in dynamic insulation diffusion deposition becomes extremely efficient for sub-micron particles. The most penetrating particle size is about 1½ µm for dynamic insulation, (Figure 1, 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 Figure 2 for the corresponding single fibre collection efficiencies shown in Figure 1. 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 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. Dynamic insulation achieves this remarkable filtration performance because the air flows are very much lower than in conventional HEPA filters.

5. FILTER CLOGGING

Dust laden air flowing through porous insulation will cause the spaces between the filter fibres at the surface to eventually become blocked. 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 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 (Figure 3) 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 to 16 years there was no noticeable decrease in air permeability compared with the values when installed [7]. The pressure increase (from 20 to 25 Pa) due to dust accumulating in mineral wool insulation is insignificant for a barn. Sallvik (1988) 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.

6. 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 to 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 higher pressure loss. The sound insulation characteristics of these thermal insulation and filtering media need to also 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. Combined with the fact that higher rates of ventilation can be employed (without creating draughts) to reduce internally generated indoor air pollution, dynamic insulation offers a means for significantly improving indoor air quality within the built environment.

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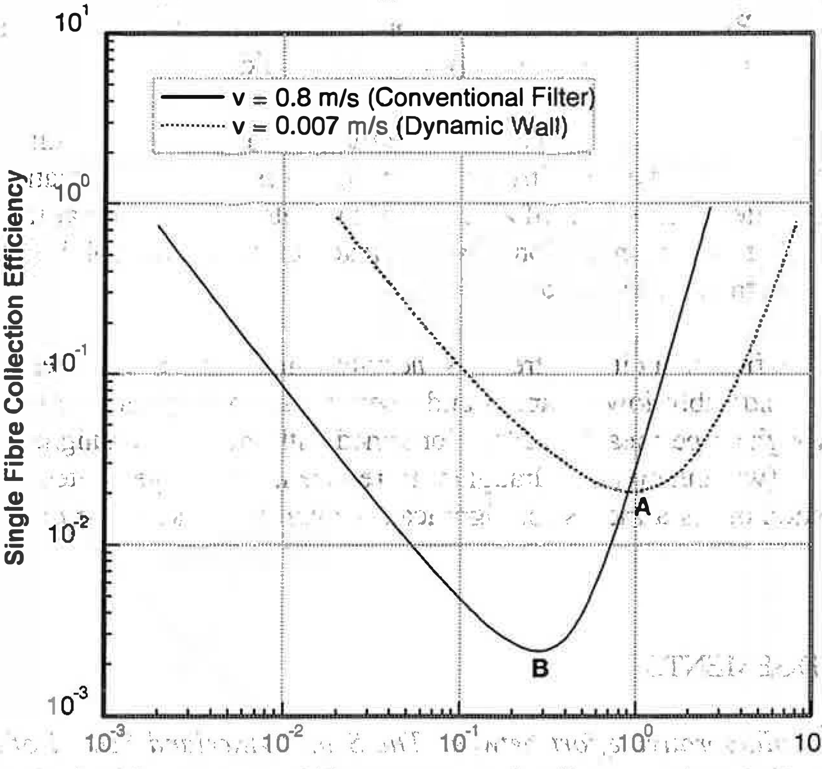

Figure 1: Effect of air speed on single fibre collection efficiency.

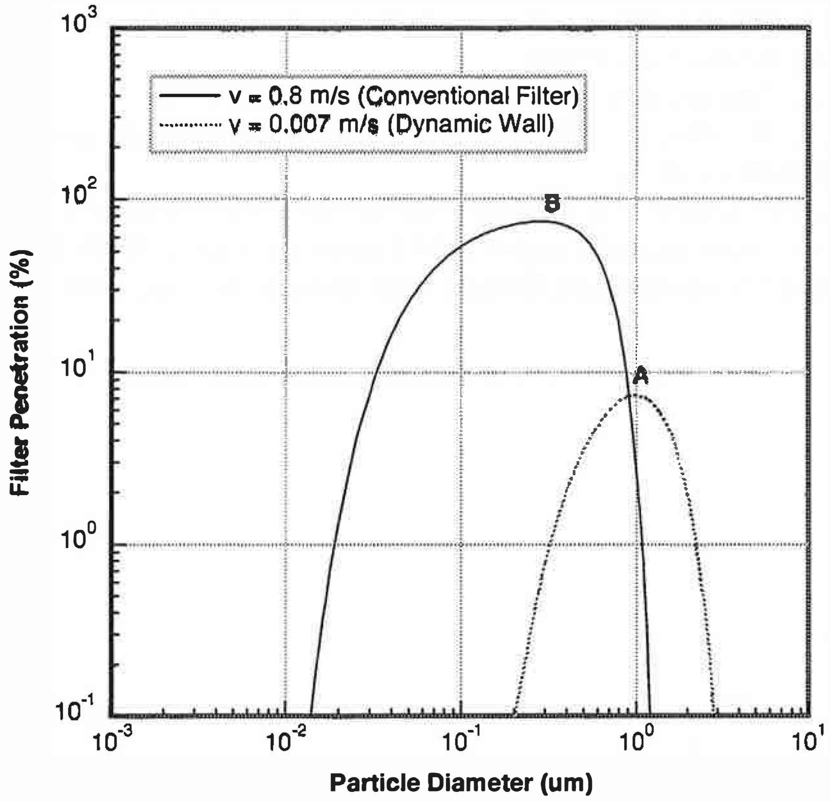

Figure 2: Effect of air speed on filter penetration.

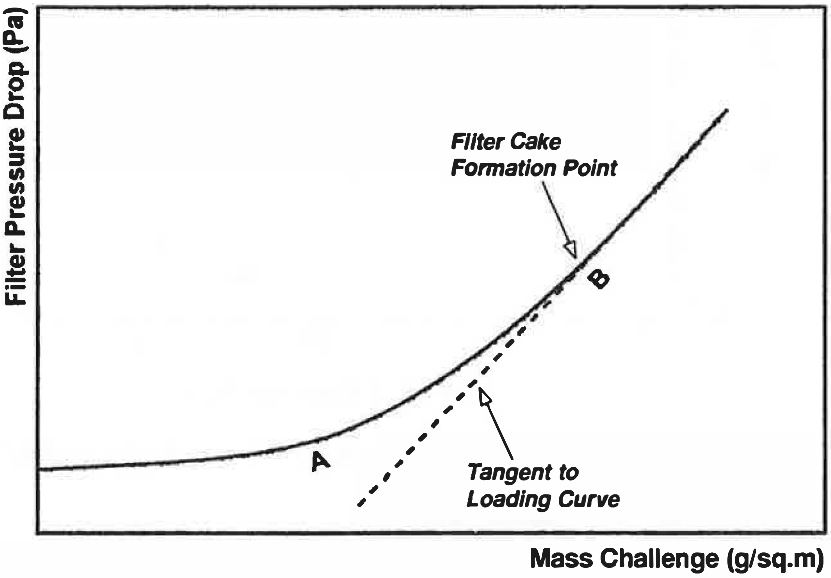

Figure 3: Pressure drop versus mass challenge per filter face area.