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AEROSOL DEPOSITION IN TURBULENT CHANNEL FLOW: IMPLICATIONS FOR ENERGY-EFFICIENT INDOOR AIR QUALITY CONTROL

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ABSTRACT

The occupants of buildings are exposed to a range of aerosol contaminants, of both indoor and outdoor origin; at present, filtered mechanical ventilation is the only effective means of airborne particulate control in polluted urban areas. Significant energy costs may be incurred, however, through the large pressure drops associated with membrane filtration. An alternative to filtration might be the enhancement of aerosol deposition on a protruding surface which is parallel to the in-coming airflow direction, but which does not significantly retard the airflow. However, current understanding of aerosol interaction with non-planar surfaces is limited.

An experimental technique is described whereby tracer-labelled aerosol particles are injected into a ducting rig which has a ribbed surface, and the spatial variation in particle deposition is studied by neutron activation analysis. Significant aerosol deposition enhancement, compared with a smooth surface was observed, for particles in the range in the range 0.7 - 7.1μm.

KEYWORDS

Aerosol, measuring techniques, ducts, energy

INTRODUCTION

In the urban environment, indoor air quality has become an issue of major concern over the past few decades since humans spend over 85% (Wallin, 1993) of their time indoors and are subjected to infiltrated outdoor air which is heavily polluted by vehicle exhausts. For mechanically ventilated buildings, the most common method for removing particulate pollutants is by membrane filtration of building intake air. The state-of-the-art in air-conditioning filtration technology is that particles of supermicrometre dimensions can be trapped effectively, but filtration efficiencies for particles of sub-micrometre dimensions are significantly less than unity; it is this particle size range which is of greatest concern in the respiratory health context. The use of any membrane filter results in a pressure drop through an air-cleaning system, so that the improvement in air quality is associated with an expenditure of energy, required to maintain an acceptable rate of airflow through the system. The current drive towards sustainability in the built environment dictates that designing a system which would effectively remove small particles from air with low associated energy usage is a high priority.

It is well known that particles flowing over protruding surfaces may be trapped by those surfaces; earlier work under representative indoor conditions, (Byrne et al, 1995) showed that even gravitationally-bound particles exhibit transport to vertical rough surfaces. The positioning of an aerosol-trapping surface in a duct system in a configuration which is parallel to the flow (rather than perpendicular, as in the case of a filter) and with limited protrusion into the flow, so that it is not significantly retarded, may form the basis of an energy-efficient air cleaning system. There is already a significant body of research (for example, Vincent and MacLennan, 1980) on aerosol deposition on obstructions in a variety of flow regimes, but the data are rarely supplemented by information on flow retardation arising from the obstructions. The possible design of a low energy filtration system relies on a detailed understanding of the interaction between particles and protruding surfaces, and also the associated pressure drop across the protruding surface, and the next section of this paper describe the design and use of an experimental system which can contribute the required information.

METHODS

An experimental channel was designed, and is shown in schematic form in Fig. 1. The system essentially consists of a blower with an associated speed controller, and a combination of circular and rectangular ducting sections. The function of the perspex sections is to allow measurement of the pressure drop along the channel, and a slot is included in each for insertion of a pilot static tube. A smooth circular duct, with an internal diameter of 160 mm, is connected to a square duct (150 mm x 150mm) comprising ten rectangular galvanised iron duct sections, and two perspex duct sections; the lengths of the galvanised and perspex sections are about 500 mm and 650 mm, respectively. The speed of air flow through the duct can be adjusted smoothly via an electronic fan speed controller, with which speeds of up to 10 ms^{-1} can be achieved.

The test surface on which aerosol deposition was measured was a series of square perspex ribs with height (*H*) 6 mm and length 145 mm which were placed transversely along the duct at prescribed intervals (i.e. pitch lengths) of 60 mm.

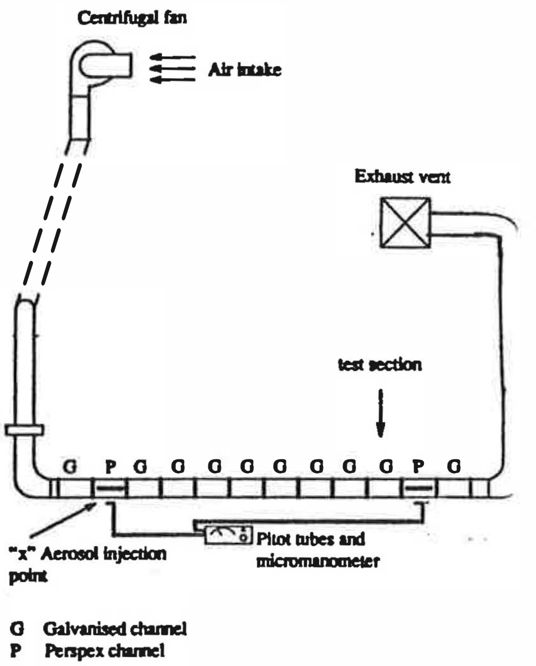

Figure 1 The experimental duct system for aerosol deposition measurements

The test section, i.e. the section whic would be analysed for deposited aerosc particles, was located at the tenth galvanise channel of the duct. It was not considere necessary to cover the whole duct system wit ribbed elements; Liou and Hwang (1992) hav shown, in a similar system, that the flo reached a fully developed state after the tent rib. In the present work, fourteen ribs we placed upstream of the measurement section.

The aerosol particle deposition velocit V_d, to a surface is defined as

$$V_d = \frac{J}{C_\infty} \qquad ($$

In the current work, where ribbed (a smooth) test surfaces are placed in a duct, *J* the particle flux to the ribbed (or smooth) surface per unit time and C_∞ is the free stream aerosol concentration.

The effectiveness with which a ribbed surface enhances aerosol deposition is coupled with a pressure drop across that surface. There are several methods for evaluating the performance of the ribbed surface by taking into account both mass flux gain due to the enhanced particle transfer (relative to a smooth surface) and the energy loss due to the increase in friction factor. In this work, since a fan-driven flow was studied, the efficiency index is chosen by comparing the particle transfer coefficient between rough and smooth ducts under the same fan power. According to this criterion, an efficiency index (for equal fan power) is defined as follows (Vilemas and Šimonis, 1985)

$$\zeta = \frac{V_{d_{rough}} / V_{d_{smooth}}}{(f_{rough} / f_{smooth})^{1/3}} \qquad (2)$$

where $V_{d_{rough}}$ and $V_{d_{smooth}}$ are the average deposition velocity along one pitch of the ribbed surface and the smooth surface respectively. f_{rough} and f_{smooth} are friction factors for the ribbed and smooth surface respectively

The friction factor, f, for a surface in a fully developed duct flow, can be written as

$$f = \frac{W/4}{\frac{1}{2}\rho U^2} \frac{\Delta P}{\Delta L} \qquad (3)$$

where W is the duct width, ρ is the air density, U is the bulk mean velocity and $\Delta P / \Delta L$ is the pressure loss per unit duct length.

Tracer aerosol particles were used in this work and the detection technique employed was neutron activation analysis (NAA). NAA is based on the principle that radioactivity of a characteristic energy may be induced in a material through bombardment with neutrons (from an external source, such as a nuclear reactor); by counting the radioactive emissions resulting from subsequent decay of the radionuclide formed, and making comparison with the emissions from a known mass of the same material, irradiated and analysed under the same conditions, the mass of material of interest in the sample can be determined. Compared to other analytical methods, NAA has a high detection sensitivity, and in aerosol science, NAA can be used as a semi-invasive particle detection technique, i.e. surfaces bearing tracer particles can be removed from the test environment for analysis, but it is not necessary to remove the deposited particles from the sample surface. When using NAA, it is desirable that the aerosol tracer in which radioactivity is induced has a reasonably short half-life, to permit rapid sample analysis and minimal radiological risk to the analyst. The rare earth elements dysprosium (^{164}Dy) and indium (^{115}In) were used since they produce radionuclides, after neutron activation, which decay with half-lives of 1.26 minutes and 54 minutes, respectively (emitting gamma radiation of 108 keV for dysprosium and of 416 keV for indium). Both ^{164}Dy and ^{115}In are rare in nature and have a high susceptibility for excitation by neutrons; a dysprosium mass of the order of 1×10^{-10} g can easily be detected after one minute's irradiation in a neutron flux of 2×10^{12} neutrons cm^{2}s^{-1}.

Four monodisperse distributions of tracer labelled particles were prepared for this work, with mass median aerodynamic diameters of 0.7, 2.5 4.5 and 7.1 μm. The supermicrometre particles used were porous silica spheres and these were dispersed using a Palas RBG-1000 powder dispersion and were labelled with dysprosium using a technique described by Jayasekera *et al* (1989). The submicrometre particles were generated by nebulising a dilute solution of indium acetylacetonate.

Spatial distributions of the particle flux, J, over the ribbed surface were determined by the following sampling arrangement: acetate sheets, less than 0.1 mm thick, were cut to fit the frontal, top and backward region of each rib and were attached by removable tape. Acetate sheets were fitted onto the smooth separation region between two successive ribs. After an aerosol deposition interval, the acetate sheets were removed for analysis. Figure 2 depicts the arrangement of samples along a pitch of ribbed duct. For each experimental run, three pitch lengths of the ribbed surface were covered with acetate sheets, thus generating 21 samples. In addition to the aerosol deposition measurements on ribbed surfaces, tracer aerosol deposition on smooth duct surfaces was also measured, for comparison.

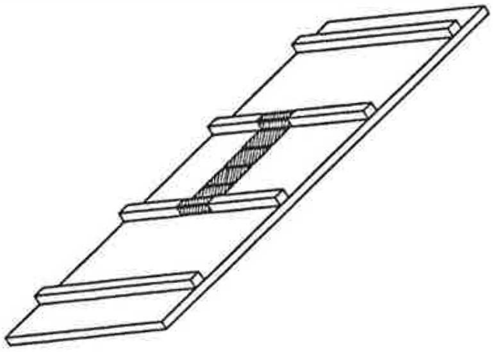

Figure 2 The arrangement of the acetate samples (shaded) on the ribbed surface

Prior to the aerosol deposition experiments, the Reynolds number, pressure drop for both smooth and ribbed surfaces, and the friction velocity for the smooth surface were calculated using either one or two pitot static tubes, which were connected to a micromanometer. The friction velocity for the smooth surface was calculated by measuring the pressure difference across the two perspex sections of the duct. The Reynolds numbe was measured by locating a pitot-static tube i the central line of the perspex channe downstream of the test section. The pressur drop across the test surface, for both th smooth and ribbed configurations, wa determined by measuring the static pressur difference across the two perspex channels; i was considered that a pressure drop based o the total pressure difference would b erroneous due to the disturbance caused by th fluctuating velocity.

A typical aerosol deposition experimen proceeded as follows: anti-static spray wa freshly applied over the acetate samples, whic had been fixed to the ribbed and plane perspe surfaces. In addition, in order to eliminate th possibility of particulate resuspension an rebounce, a thin coating of liquid paraffin c was applied evenly onto the sample surface Air at room temperature was then drawn int the duct and the flow speed was fixed at a average of 4.4 m/s (which corresponded to Reynolds number of 40,000). Aerosol partic were injected, at a height of 75mm wi respect to the duct floor, into the perspe duct section which was upstream of the tes The aerosol concentration in the duct was the determined by isokinetic sampling; t sampling probe was placed at the centre line the downstream perspex channel. Owing the high detection sensitivity of NAA, ea experiment ran for only 15 to 20 minutes. T acetate samples were then removed from t ribbed and plane perspex surfaces and we subjected, together with the filter paper fr the isokinetic air sampler, to neutr activation analysis.

RESULTS

Figures 3 and 4 shows the spatial distribution in aerosol deposition velocity along the ribbed surface for the largest and smallest particles studied: 0.7µm and 7.1 µm respectively. Comparison with the results over a smooth surface in the duct (Lai, 1997) indicates that significantly greater aerosol deposition occurs on the ribbed surface than on the smooth surface, and deposition is dominant on the front face of the rib, and also on the top face. Different deposition mechanisms are thought to apply for the two particle sizes shown: the deposition of the submicrometre particles is likely to be dominated by turbulent diffusion, and sedimentation and inertial impaction are likely to be the major influences on deposition for the 7.1 µm particles.

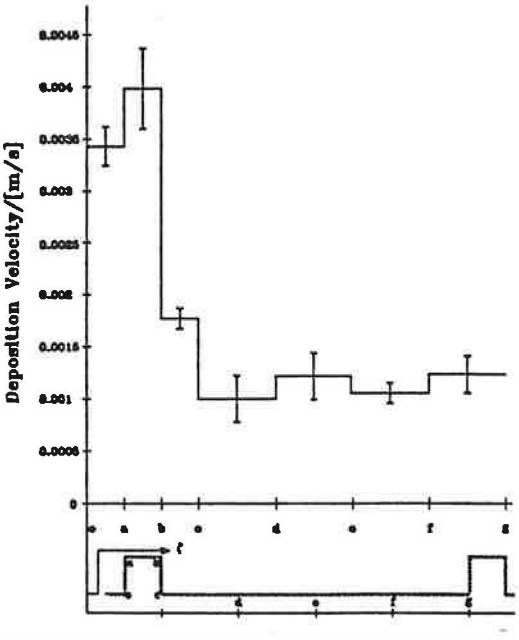

Figure 3 Spatial distribution in aerosol deposition over the ribbed surface: 0.7 µm particles

For the present set-up, the friction factor ratio f_{rough}/f_{smooth} had the value 3.2, and for all four particle sizes tested, ζ, the efficiency index, evaluated using Equation (2), was found to have a value close to 2. Since ζ is greater than unity over the particle size range studied, it suggests that the ribbed surface is an energy efficient method of enhancing particle deposition.

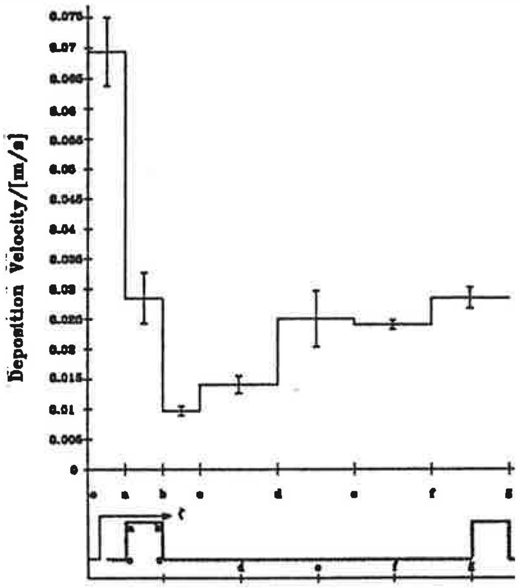

Figure 4 Spatial distribution in aerosol deposition over the ribbed surface: 7.1 µm particles

DISCUSSION

Experiments have been carried out to aid in understanding aerosol interaction with surfaces, with the aim of contributing to knowledge which could be used in the design of low-energy air cleaning systems. Aerosol deposition on a ribbed surface in a duct has been studied, and the use of sensitive tracer detection techniques has allowed the measurement of spatial variations in aerosol deposition along the ribbed surface. This detailed deposition information, supplemented with a knowledge of the pressure drop across the duct which is associated with the ribbed surface, represents an important advance in current knowledge.

In terms of low-energy aerosol deposition enhancement, a square ribbed surface was seen to perform well under a single flow condition, for a limited range of particle sizes. It is suggested that further investigations should be carried out with the aim of optimal manipulation of the duct surface, so that aerosol deposition is maximised and the pressure drop in the duct is minimised. Further work should focus on other airflow conditions, a wider range of particle sizes, and different configurations of ribs or small obstructions. However, in evaluating the feasibility of an obstructed duct surface as a low energy alternative to membrane filtration, it is important that the implications for cleaning or replacing an intentionally-soiled duct surface are considered.

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