Particle deposition in ventilation duct onto three-dimensional roughness elements

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Abstract

Gaining insights on particle deposition onto ventilation duct has many important applications. One key pathway by which outdoor polluted air enters the indoor environment is through mechanical ventilation ducts. An experimental system was designed for the study of particle deposition on regular arrays of uniform elements (in the form of discrete protrusions) in a turbulent ventilation duct flow using monodisperse tracer small particles, in the range 0.7–7 \( \mu \)m. The Reynolds number for the test conditions was 44,000 in the 150 mm square duct. Four different types of uniform roughness elements were tested. Compared to earlier measurements in the same duct system involving smooth or ribbed surfaces, a significant increase (up to 74 times) in deposition velocity onto the regular roughness elements is observed. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Human exposure to small suspended particles may contribute severe respiratory damage, cardiovascular disease morbidity and mortality [1–3]. Epidemiological evidence suggests a positive correlation between outdoor PM\(_{10}\) concentrations and mortality in urban areas [1,4]. This finding is still a puzzle to many investigators: people spend over 90% of their time indoors [5] and hence they are exposed mainly to indoor particles. For mechanically ventilated buildings, one plausible justification is that outdoor air enters indoors through the ventilation duct system. The degree to which outdoor particles penetrating through the ventilation system depends strongly on flow characteristics, particle physical characteristics, ventilation filter collection efficiency, etc. In order to estimate how many outdoor dust particles are carried indoors, both particle deposition and resuspension should be considered. The rate of particle resuspension inside a ventilation duct depends on numerous factors. Among these ventilation speed, particle size, particle density, shape, surface texture are the key aspects. In the present work, we only focus on the particle deposition on the duct, which depends strongly on physical particle size.

Most previous research has concentrated only on the statistical properties of air and solid particles under high-speed turbulent flow in small channels [6–8] and the results cannot be directly applied to gain knowledge of particle deposition on a ventilation duct system. In ventilation ducts, roughness scales of several millimeters are not uncommon, but despite this, studies of particle deposition in channel flow have largely been confined to smooth surfaces. A few exceptions exist, but these focus on large-scale obstructions. Vincent and MacLennan [9] showed that incorporating obstructions in collecting electrodes significantly improved the overall performance of an electrostatic precipitator. Suh and Kim [10] reported a similar effect, and found that the enhanced precipitator performance was most pronounced for particles of the order of 5 \( \mu \)m. Li et al. [11] simulated particle dispersion and deposition in a duct obstructed with large rectangular and trapezoidal blocks and their results showed that large particles deposited readily on the front faces of the obstructions due to impaction and interception. Lai et al. [12] measured the particle deposition of 0.7–7.1 \( \mu \)m particles on two-dimensional ribs in a duct, and found that on average, particle deposition rate increased by a factor of 2–3 relative to smooth surfaces.

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The research cited above is complemented by a small number of studies of particle deposition on small-scale roughness. Wells and Chamberlain [13] measured particle deposition on filter paper-lined pipe walls and reported that the rate of deposition was enhanced, relative to that on smooth walls, by about two orders of magnitude. The simulations of Li and Ahmadi [14] of particle deposition on various scales of sand-grain roughness produced a similar result. El-Shobokshy [15] measured particle deposition onto machinery-ground brass tubes with small mean roughness heights (7 and 20 \( \mu m \)). The measured deposition velocities, compared to those measured on a smooth glass tube, were more than one order of magnitude higher. Guha [16] proposed a unified theory for particle deposition and carried out simulations that also supported the finding of a large increment in particle deposition on surfaces with small-scale roughness. Recently, Lai et al. [17] measured particle deposition onto one type of regular array of three-dimensional roughness elements in a ventilation duct for four particles sizes, ranging from 0.7 to 7.1 \( \mu m \). They observed that the particle deposition rate increased by a factor of 6–18 relative to smooth surfaces.

Intuitively, information relevant to mass transfer to rough surfaces should be provided by the results of heat transfer studies and the work of Hahn et al. [18] supports the use of the heat/mass transfer analogy for understanding the deposition of very small particles. However, for larger particles, the use of the analogy is of limited value because there is a significant difference in magnitude between the dimensionless diffusion parameters for heat and mass transfer: the Prandtl number (\( Pr \)) has a value of about 0.7 for air, but for 1 \( \mu m \) particles the Schmidt number (\( Sc \)) can be as high as 500,000 and increases rapidly with particle size. This implies that heat transfer studies contribute little to developing an understanding of particle deposition on rough surfaces.

Due to the limited experimental data available on particle deposition on rough surfaces, the main objective into the present work is to gain more physical insights, through experiment, into the mechanisms of particle deposition enhancement on small-scale roughness elements. As already mentioned in the previous publication [17], with the aid of using regular array three-dimensional roughness elements, the study of particle deposition can be performed more systematically by varying individual dimensions of the elements. This paper extended the previous work by studying the rate of particle deposition for three additional types of regular arrays of three-dimensional roughness elements and the results were compared to the previous roughness elements (referred to as “base-type” in this work). Implications for human exposure assessment are also highlighted and discussed.

2. Background

Many of the background details on the turbulent flow structure has been introduced and discussed in the previous study [17] and will not be repeated. A general conclusion drawn from experimental evidence is that, for a fully developed turbulent duct flow, three layers exist, each of which requires a different equation for the velocity distribution. For turbulent flow over a rough surface, many experimental studies have investigated the flow behavior on walls roughened by various types of elements. Nikuradse’s [19] classical experiments offered important insights for flow over sand-grained surfaces, showing that it could be classified into three flow regions, i.e. (i) hydraulically smooth (ii) transition and (iii) completely rough regions. The extent to which a particular flow condition is actually affected by roughness depends on the parameter “dimensionless roughness height”. It should be noticed that although the existence of the transition region has generally been ignored, it is the most crucial layer for consideration in efforts towards optimizing heat/mass transfer [20,21]. For many existing heat transfer/mass transfer enhancement studies, flow considerations have focused on completely rough regions [22,23].

An experimental system designed to study particle deposition on discrete protrusion elements in a square duct will be described in the next section. The results are presented later in the paper, and are discussed in the context of the flow regions described above.

3. Experimental set-up and procedure

Fig. 1 is an overall schematic of the experiment system designed for the present study. The test rig essentially consists of a blower with an associated speed controller, and a combination of circular and rectangular ducting sections. The duct is of side 150 mm and the test section is 0.5 m
Based-type

Type 2

Type 3

Type 4

All dimensions are in millimeters

Fig. 2. Arrangement of the roughness elements in the test channel.

Fig. 3. Dimensions of the three-dimensional roughness elements sampled. All the units are in millimeters.

Prior to each experiment, anti-static spray and a thin coating of liquid paraffin was applied to the roughness elements, to eliminate (a) the effects of static charge and (b) the occurrence of rebound and resuspension of particles, respectively [12]. Following these preparations, a typical experiment proceeded as follows: air at room temperature was drawn into the duct and the flow speed was fixed by a variable speed controller at an average of 4.4 m s\(^{-1}\); this speed falls within the range of operation of conventional
ventilation duct systems. Particles were injected into the upstream Perspex duct (marked as “X” in the Fig. 1). The time-integrated particle concentration was determined by isokinetic sampling; the suction flow rate of the sampling probe which was placed at the center line of the downstream Perspex channel had been pre-adjusted and set to approximately 9.51 m\(^{-1}\) to ensure that the velocity at the tip of the inlet was equal to the local mean gas velocity. Owing to the high detection sensitivity of the system used to analyze the tracer particle, each experiment ran for only 15–20 min. The samples were then removed from the Perspex surfaces and were subjected, together with the filter paper from the isokinetic air sampler, to neutron activation analysis.

4. Method of analysis

The tracer particle analysis method used in this work 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 analyzed under the same conditions, the mass of material of interest in the sample can be determined. Compared to other analytical methods, i.e. fluorescent spectrometry method which is the most common tracer detection technique, NAA has a high detection sensitivity, and since the energy of the induced radiation is characteristic of a particular material, it can be used for identification and mass determination of a wide range of materials. The principles of NAA are further elaborated in Parry [26]. The rare-earth elements dysprosium (\(^{164}\)Dy) and indium (\(^{115}\)In) were considered suitable particle tracers for the present work. Full details of the tracer characteristics are presented elsewhere [12,17] and will not repeated here.

Four monodisperse distributions of tracer labeled particles were prepared for this work, with mass median aerodynamic diameters of 0.7, 2.5, 4.5 and 7.1 \(\mu\)m, and respective geometric standard deviations of 1.36, 1.50, 1.10 and 1.10. The supermicrometer particles used were porous silica spheres, supplied by Phase Separations Ltd (Clwyd, UK). The particles were dispersed using a Palas RBG-1000 powder dispersion generator (Karlsruhe, Germany) and were labeled with dysprosium using a technique described by Jayasekera et al. [27]. The particle was passed through a tube containing a 0.4 MBq Americum-241 radioactive source; using the calculations of Cooper and Reist [28] it was estimated that, for the particle flow rate used, the ratio of the residence time of the particle in the tube and the characteristic source strength used was greater than unity, so that particle Boltzmann charge equilibrium would be reached. The submicrometer particles were generated by nebulizing a dilute solution of indium acetylacetonate.

5. Data analysis

Particle deposition was quantified in terms of a deposition velocity, \(V_d\) (m s\(^{-1}\)), and it is defined as

\[
V_d = \frac{J}{C_\infty},
\]

where \(J\) is the particle flux (g m\(^{-2}\) s\(^{-1}\)) to the surface and \(C_\infty\) (g m\(^{-3}\)) is the free stream particle concentration. In the present work, where neutron activation analysis was used to determine the tracer particle mass on roughness elements and on air filters, the following expressions were used:

\[
J = \frac{M_{3D}}{A_{3D}t},
\]

\[
C_\infty = \frac{M_{\text{filter}}}{Q},
\]

where \(M_{3D}, M_{\text{filter}}\) are the tracer particle masses detected on a single roughness element and a single air filter, respectively. \(t\) is the sampling time and \(Q\) is the total volumetric flow through the air filter, samples. It should be noted that \(A_{3D}\) is the smooth base area of the rough surface sample and not the total area available for particle deposition; this is the general practice adopted in heat transfer research [29] and has the advantage of enabling direct comparison of transfer coefficients for different configurations.

6. Results and discussion

Fig. 4 shows the particle deposition velocity, for four particle sizes (mass medium aerodynamic diameter), on arrays of uniform protrusion for the base-type roughness elements [17]. Results for the smooth and two-dimensional ribbed duct surfaces [12] are also shown for comparison. It can
be clearly seen that the presence of the three-dimensional roughened surface results in a higher particle deposition velocity than in the case of the ribbed surfaces, particularly for submicrometer particles. As expected in the particle size range studied (from diffusion dominated to gravitational settling dominated regime), the particle deposition velocity is seen to increase with particle size.

The results presented above indicate that the particle deposition velocity onto the regular array of roughness elements is significantly greater than in the case of the smooth and the ribbed surfaces studied earlier. In order to gain more insight into the mechanisms occurring, the thickness of viscous sublayer and the flow structure in the vicinity of the test surfaces must be understood. As discussed earlier, for a fully developed turbulent channel flow, it is well known that the longitudinal velocity gradient is very steep inside the viscous layer, decreasing in the buffer and turbulent core region and becoming zero in the centerline. Since for small particles $Sc \gg 1$, it means that the thickness of the particle concentration boundary layer is significantly less than the thickness of the viscous layer. It can be inferred from previous work [30] that the dimensionless concentration boundary thickness (which was arbitrarily defined as the thickness at which the ratio of the concentration to the bulk concentration equals 0.9) has a value of $y^+ = 0.7$ for 0.1 μm particles and decreases with increasing particle size. $y^+$ is defined as $yu_s/
u$ where $y$ is the distance measured from the boundary, $\nu$ is the kinematic viscosity of the air and $u_s$ is the friction velocity. The methodology for measuring $u_s$ is described in a previous paper [30].

Although the work of Lai and Nazaroff [30] was focused on indoor deposition of particles, the calculation of concentration boundary thickness is considered valid for both well-mixed chamber and channel flow situations. It implies that most of the resistance for particle deposition is concentrated within a very thin layer above the surface, which has been suggested by previous heat transfer experiments [31,32]. If this thin layer can be completely destroyed or at least made thinner, the transportation progress can be greatly enhanced [17]. The dimensionless roughness height for the base-type elements under the same flow condition was estimated to be 37 and was immediately outside the buffer region. The protruding surface prevents either the build-up of the boundary layer or the thinning of the boundary layer but without causing excessive drag force by the turbulent flow because the roughness elements are submerged below the turbulent layer which produces a lower mean flow velocity. This explains why the friction factor of the three-dimensional roughness elements is lower than the value obtained when two-dimensional ribbed surfaces were investigated [17].

For the three additional regular arrays roughness elements studied, only two particle sizes, 0.7 and 7.1 μm were tested. Figs. 5 and 6 show the deposition velocity results for 0.7 and 7.1 μm particles, respectively. For the 0.7 μm particle size, it can be seen that, compared with the base-type roughness elements, much higher deposition velocities were found for the type 4 elements. The ratio of deposition on type 4 elements to smooth surfaces is approximately 74. However, taking the experimental error into account, the difference in deposition velocity for the type 2 and 3 elements compared to the base-type is not obvious.

For all types of roughness elements studied, the maximum variation of the deposition velocities for 7.1 μm particle size was only 38%. Intuitively, inertial impaction was thought to be an important deposition mechanism for heavy particles and therefore for the type 2 and the type 4 elements, which have twice as much frontal deposition area as the base-type element, the particle deposition velocity was expected to significantly increase. This was not, however, reflected in the measurement results.

Although previous workers [11,33] have observed that inertia impaction of particles strongly aids the deposition process, their measurements involved large protrusions which penetrated both the sublayer and the buffer layer and emerged into the turbulent layer. The turbulent layer is associated with high turbulent flow velocity and hence
the impaction effect is very effective there, but it is not true when the element is submerged into the sub- and buffer layers, as in the present case. The mean flow velocity inside the sublayer is approximately 10% of the main flow [34] and therefore the deposition mechanism by inertial impaction is a less influential parameter. This is a plausible explanation for the present experimental observations. Detailed CFD simulations and Laser Doppler Velocimetry measurements in the vicinity of the roughness surface are required for a more complete understanding.

Summarizing the results obtained for all roughness element configurations, it is found that for the submicrometer particles, the flow structures in the vicinity of the roughness elements influence particle deposition significantly while for supermicrometer particles, the influences of roughness configuration on particle deposition were observed to be less.

One additional point should be noted. The highest deposition velocity for 0.7 μm particles occurred when type 4 roughness elements were used, but this configuration gave the lowest deposition velocity for 7.1 μm particles. On the other hand, the particle deposition velocity was the lowest for 0.7 μm and was the highest for 7.1 μm particles on the base-type elements. These observations imply that there is no single roughness configuration that can maximize particle deposition for all particle sizes.

The results described above contribute significantly to a better understanding of human exposure to airborne particulate pollution. Particle deposition on the components of a ventilation system is an important factor in determining overall particle penetration through a forced ventilation system. Inferring from the current results, it is considered that small-scale roughness on a ventilation duct could considerably enhances deposition for the submicron particle size.

It is well recognized that for particle sizes ranging from 0.1 to approximately 2 μm (accumulation mode particles), neither diffusion nor gravitational settling removal mechanisms dominate, and it is very difficult and energy is not sufficient to filter out these particles by use of fibrous media [35,36]. Furthermore, for reasons of energy conservation, most forced ventilation systems in commercial buildings employ low to medium grade fibrous filters, which have very low removal efficiency for accumulation mode particles, i.e. as low as 2–10% for 0.1–1 μm. [37]. One potential energy-efficient filtration solution is utilization of an electrostatic precipitator. However, these require greater maintenance than conventional filtration systems, and are not yet widely employed in air conditioning systems in commercial buildings.

Finally, it should be emphasized that it is a very challenging problem to model particle penetration through ventilation ducts because many physical factors of the air conditioning system, and physical and chemical characteristics of particles, affect the rate of particle deposition and resuspension. Even for the simplest air conditioning ducting system, there are many bends and dampers, and these will further complicate the air flow pattern and hence the particle deposition as large particles cannot follow fluid streamlines and will impact on bends.

7. Conclusions and remarks

Particle deposition on roughness elements was studied experimentally (using neutron activatable-tracer labeled particles) for a fully developed turbulent flow field in a channel with one surface (horizontal upward facing) roughened by four different regular arrays of uniform elements. The key conclusions are as follows:

Generally, it was observed that the three-dimensional roughness elements enhanced particle deposition to a greater degree than the two-dimensional ribbed surface used in the same channel in an earlier investigation [12]. This may be due to the effective destroying of the development of the boundary layer which is the region of highest resistance for transportation of heat and mass.

Preliminary results show that deposition for submicron particles was significantly higher for all three-dimensional roughness elements tested than for the smooth surfaces. The ratio ranges from 17 (base type) to 74 (type 4). However, the deposition velocity for supermicron particles for all three-dimensional roughness elements were approximately the same. In order to provide more physical understanding of particle deposition onto rough surfaces, detailed experiments and CFD modeling in the vicinity of the elements are necessary.

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References


