Aerosol deposition in turbulent channel flow on a regular array of three-dimensional roughness elements

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Abstract

Understanding particle deposition onto rough surfaces is important for many engineering and environmental applications. An experimental system was designed for the study of aerosol 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 0.7–7.1 μm. The Reynolds number for the test conditions was 44,000 in the 150 mm square duct. The roughness elements were arranged at two different orientations with respect to the airflow direction and the aerosol deposition velocity and pressure drop were measured for both orientations. Compared to earlier measurements in the same duct system involving smooth or ribbed surfaces, a significant increase in deposition velocity onto the regular roughness elements is observed. In addition, the associated pressure loss penalty is lower than in the presence of the roughness elements than in the presence of the ribbed surfaces. This may be attributable to the small dimensionless roughness height of the elements, which results only in a moderate distortion of the flow structure near the surfaces. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The phenomenon of particle transport in directed airflows has been studied extensively over the past few decades. However, to date, most of the work has been focused on the statistical properties of air and solid particles under high-speed turbulent flows in small channel systems (e.g. Soo et al.,

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1960; Brooke et al., 1992; Kulick et al., 1994) and the results cannot be directly applied to gain knowledge of particle deposition on surfaces. The interaction of particles with surfaces has important implications in the context of human health. In some situations, e.g. in cold winters with low building ventilation rates, reduction in inhalation exposure to air pollution by the occurrence of aerosol deposition on surfaces may be significant (Nazaroff and Cass, 1989). In the case of specific atmospheric contamination episodes, Fogh et al. (1997), by considering the effect of indoor aerosol deposition, have shown that the benefits, in terms of reduction in inhalation exposure, achieved by staying indoors, may be as high as 80%. However, in other contexts, aerosol deposition on surfaces may have detrimental effects. Particle losses in sampling lines give rise to errors in determining aerosol concentrations (Muyshondt et al., 1996). Further, aerosol deposition on the surfaces of cultural artifacts may lead to irreparable soiling and degradation (Nazaroff et al., 1990).

Most surfaces encountered in practice are not fully smooth: in the indoor environment, surface roughness in the range 0.01–0.5 mm occur (Thatcher, 1996) whereas in ventilation ducts, roughness scales of several millimeters may exist. Despite this, studies of aerosol 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 (1980) showed that incorporating obstructions in collecting electrodes significantly improved the overall performance of an electrostatic precipitator. Suh and Kim (1996) reported a similar effect, and found that the enhanced precipitator performance was most pronounced for particles of the order of 5 μm. Li et al. (1994) 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. (1999) measured the aerosol deposition velocity of 0.7–7.1 μm particles on two-dimensional ribs in a duct, and found that on average, the deposition velocity increased by a factor of 2–3 relative to smooth surfaces.

The research cited above is complemented by a small number of studies of aerosol deposition on small-scale roughness. Wells and Chamberlain (1967) measured aerosol deposition on filter paper-lined pipe walls and reported that the deposition velocity was enhanced, relative to that on smooth walls, by about two orders of magnitude. The simulations of Li and Ahmadi (1993) of aerosol deposition on various scales of sand-grain roughness produced a similar result. El-Shobokshy (1983) measured particle deposition onto machinery-ground brass tubes with small mean roughness heights (7 and 20 μm). The measured deposition velocities, compared to those measured on a smooth glass tube, were more than one order of magnitude higher. Recently, Guha (1997) proposed a unified theory for particle deposition and carried out simulations that also supported the finding of a large increment in aerosol deposition velocity on surfaces with small-scale roughness. However, none of the measurements or simulations provided a detailed explanation of why a high deposition velocity should result.

In the analogous field of heat transfer research, a few studies on surfaces with small-scale roughness also exist. The investigations of Dipprey and Sabersky (1963) focused on heat transfer in a small tube lined with closely packed sand grains. More recently, Han et al. (1993) measured the heat transfer coefficient and friction factor on wedge-shaped and delta-shaped elements in a square channel under turbulent flow conditions. In all cases, heat transfer enhancement of 3–4 times relative to the smooth duct was reported (compared to increments of several orders of magnitude in the case of particle deposition).
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. (1985) 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 μm particles the Schmidt number (Sc) can be as high as 500,000 and increases rapidly with particle size. It 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 of the present work is to gain a physical insight, through experiment, of the mechanisms of aerosol deposition enhancement on small roughness elements. In general, three-dimensional roughness elements may be divided into two categories. The first category, referred to as ‘sand-grained’ or ‘sand-type’ roughness, consists of tightly packed roughness elements with a mean roughness height and a standard deviation height. The second type of roughness has well-defined dimensions in three co-ordinates. The second category was chosen for investigation in the present work, because there is greater scope for later research e.g. by systematically varying individual dimensions of the elements (i.e. width, height, spacing) and investigating the effect on aerosol deposition.

2. Background

2.1. Turbulent flow structure

A general conclusion that may be 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. Although not rigorously defined, the thickness of the three layers is commonly expressed as follows (Rohsenow and Choi, 1961):

\[
0 \leq \frac{yu_\ast}{v} \leq 5 \quad \text{viscous sublayer,} \quad (1a)
\]

\[
5 \leq \frac{yu_\ast}{v} \leq 30 \quad \text{buffer layer,} \quad (1b)
\]

\[
30 \leq \frac{yu_\ast}{v} \quad \text{turbulent core,} \quad (1c)
\]

where \( y \) is the distance measured above from the boundary, and \( v \) is the kinematic viscosity of the transport fluid. \( u_\ast \) is the friction velocity (shear stress velocity), an important parameter for describing turbulent channel flow or boundary layer flow and is defined as

\[
u_\ast = \sqrt{\frac{\tau_w}{\rho}}, \quad (2)\]
Here, $\tau_w$ is the wall shear stress and $\rho$ is the density of the fluid. For a smooth surface, the physical significance of $u_*$ can be interpreted as being equal to the fluctuation velocity in the $y$ direction (Davies, 1972). The magnitude depends on a number of parameters, notably, the nature of the surface; for a rough surface, it is related to the packing density of the protrusions, the shape and height of the protrusions and the mean flow velocity over the roughness elements.

The zone immediately adjacent to a surface is a layer of fluid that, because of the damping effect of the surface, remains relatively steady even though most of the flow is turbulent. This layer is termed the viscous sublayer and although it is very thin, it plays a significant role in the transportation process since it has the highest resistance to heat/mass transport (Dawson and Trass, 1972; Kozlu et al., 1992). It can be inferred from earlier studies of smooth surfaces that for particles greater than 0.01 $\mu$m, the sublayer contributes over 93% of the total resistance (Lai and Nazaroff, 2000).

2.2. Turbulent flow over rough surface

Many experimental studies have investigated the flow behavior on walls roughened by various types of elements. Nikuradse’s (1933) 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 dimensionless roughness height, $e^+$, (or roughness Reynolds number, $Re_e$), defined by

$$e^+ = \frac{e u_*}{v},$$

where $e$ is the typical height of a protrusion. Webb (1979) concluded that to understand the performance characteristics of rough surfaces, one must accept that $e^+$ rather than $Re$ is the significant flow variable.

2.2.1. Hydraulically smooth region

If the protrusion element is immersed completely within the viscous sublayer, i.e. $e^+ < 5$, the roughness will not significantly affect the nature of the turbulent flow in the wall region. Dawson and Trass (1972) used electrochemical techniques to measure the mass transfer coefficient for a series of geometrically similar rough surfaces, in the form of V-shaped grooves. They concluded from their results that the roughness has little or no effect on mass transfer (it should be noted that they defined the hydraulically smooth region, as $e^+ < 3$). In addition, Kozlu et al. (1992) carried out a heat transfer augmentation study using streamwise-periodic microgrooves in a smooth channel and observed that the microgrooves had negligible effect on heat transfer augmentation for $e^+ < 10$.

2.2.2. Transition region

In the transition region, $5 < e^+ < 30$, the protrusion elements emerge from the viscous sublayer and extend into the buffer zone. Although the existence of this layer has generally been ignored, it is the most critical layer for consideration in efforts towards optimizing heat/mass transfer (Rabas, 1989; Suzuki, 1995).
2.2.3. Completely rough region

The fully rough region corresponds to $e^+ > 70$. The near wall flow structure is completely destroyed by the presence of the protrusion elements and the largest part of resistance due to flow is the form drag which acts on them. For this reason, the law of resistance becomes quadratic (Schlichting, 1979). The eddies caused by the presence of the roughness elements will dominate the turbulent motion close to the wall.

The next section of this paper describes an experimental system designed to study aerosol deposition on discrete protrusion elements in a square duct. 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 sample arrangement

Figure 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 long. The rig was used previously for studies of aerosol deposition on ribbed surfaces, and full details of its design are presented elsewhere (Lai, 1997; Lai et al., 1999) and will not be repeated here.

Fig. 1. Schematic diagram of the ventilation duct experimental set-up.
Three-dimensional regular arrays of uniform elements were arranged on the horizontal upward-facing surface of the duct. Although it was desirable to cover the whole duct with the roughness elements, in order to create a homogeneous environment for the flow to develop along the duct, limited resources made it impossible to fabricate sufficient quantities. However, Sparrow et al. (1982) and Jubran et al. (1996), in their forced convection channel flow experiments, both showed that the flow reached a fully developed state after five rows of three-dimensional roughness elements. Therefore, it was considered feasible to adopt a similar strategy and in the present work, the test elements were surrounded by a sufficient number of the same roughness elements to provide adequate pathways for the flow to fully develop before reaching the elements of interest. The detailed configurations of the roughness element arrays are described later in this section. The duct system can be considered as consisting of five sections: the roughness-free inlet section, the flow developing section, the test section, the exit section (containing roughness elements) and the smooth final exit section. The dimensions of the roughness elements are shown in Fig. 2.

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 (Lai, 1997). 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$^{-1}$. Aerosol particles were injected into the upstream perspex duct (marked as ‘×’ in Fig. 1). The aerosol concentration was determined by isokinetic sampling; the suction flow rate of the sampling probe which was placed at the centerline of the downstream perspex channel had been pre-adjusted and set to approximately 9.51 min$^{-1}$ to ensure the velocity at the tip of the inlet was equal to the local mean air velocity. Owing to the high detection sensitivity of the system used to analyze the tracer aerosol (described later), each experiment ran for only 15–20 min.

As mentioned earlier, the roughness elements did not cover the entire duct in the present work and the friction factor was therefore determined by an indirect method and with the aid of previous results generated with ribbed surfaces in the same duct (Lai et al., 1999). The pressure drop across the duct roughened with regular arrays of uniform elements was first measured using two pitot
tubes connected to a micromanometer (Furness, UK). The roughness elements were then replaced by the ribbed surfaces used in the previous study (Lai et al., 1999) and the pressure drop was recorded. The total area covered by the ribs was kept approximately the same as that covered by three-dimensional elements in the previous case (~ 1 m). The analysis of these data is described later.

In order to study the influence of the orientation of the roughness elements, relative to the flow, on particle deposition velocity, a modular design was adopted, in order to allow flexibility in arranging the elements. Three different module sizes were used; these were (a) 145 × 145 mm, (b) 35 × 20 mm and (c) 12 × 6 mm, respectively, where (c) is the unit which is sampled for deposited aerosol particles. The arrangement of the roughness elements in the test section of the duct for the orientation which is parallel to the airflow (hereafter referred to as the ‘parallel’ scheme) is depicted in Fig. 3. In the parallel scheme, there were 42 roughness elements upstream of module (b). For the parallel orientation, in order to reduce the flow instability caused by flow discontinuity between the modules, only the middle five elements of module (c) were actually sampled.

Figure 4 depicts the arrangement of roughness element modules in the orientation which was perpendicular to the airflow in the duct (hereafter referred to as the ‘perpendicular’ orientation). It can be seen from the figure that four samples can be obtained for analysis in this case. In the
perpendicular scheme, there were 35 roughness elements upstream of the first sampling unit. It should be noted that in both orientations, the total area of the elements on which deposition can occur is identical.

4. Tracer analysis methodology

The tracer aerosol analysis method used in this work is 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, 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 (1991).

The rare-earth elements dysprosium (\(^{164}\text{Dy}\)) and indium (\(^{115}\text{In}\)) were considered suitable aerosol tracers for the present work since both elements occur naturally in low concentrations and produce short-lived radionuclides, following neutron activation. Four monodisperse distributions of tracer labeled particles were prepared, with mass median aerodynamic diameters of 0.7, 2.5, 4.5 and 7.1 \(\mu\text{m}\), 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 labeled with dysprosium using a technique described by Jayasekera et al. (1989) and were dispersed using a Palas RBG-1000 powder dispersion generator (Karlsruhe, Germany). The aerosol was passed through a tube containing a 0.4 MBq \(^{241}\text{Am}\) radioactive source; using the calculations of Cooper and Reist (1973) it was estimated that, for the aerosol flow rate used, the ratio of the residence time of the aerosol in the tube and the characteristic source strength used was greater than unity, so that aerosol charge equilibrium would be reached. The submicrometer particles were generated by nebulizing a dilute solution of indium acetylacetonate.

5. Data analysis

As mentioned earlier, the friction factor for the duct which had one surface roughened with three-dimensional elements was determined by combining the results of pressure drop measurements made with ribbed and rough surfaces present separately in the duct. The friction factor of the duct with the 3D surfaces present on one surface, and with three smooth surfaces, \(f_{3D-3S-1R}\) can then be approximated as

\[
f_{3D-3S-1R} \approx f_{2D-3S-1R} \frac{\Delta P_{3D-3S-1R}}{\Delta P_{2D-3S-1R}},
\]

where \(f_{2D-3S-1R}\) is the friction factor for the duct containing one-ribbed surface and three smooth surfaces (Lai et al., 1999), and \(\Delta P_{3D-3S-1R}\) and \(\Delta P_{2D-3S-1R}\) are the pressure drops across the duct when its one surface was covered with three-dimensional and ribbed surfaces, respectively. All values corresponded to the same Reynolds number, 44,000. The value calculated for the quantity \(f_{3D-3S-1R}\) was 0.012.

In using Eq. (4) to calculate the friction factor, two assumptions were made. Firstly, it was assumed that the pressure drop across the smooth portion of the ducts in both situations (i.e. ribbed and roughened) was small compared with that across the rough/ribbed portion. This assumption was justified by two factors: firstly, the length of the rough/ribbed portion and the smooth portion was approximately the same. Secondly, with similar flow parameters to those used in the present work, Chandra and Cook (1994) found that the ratio of the friction factor for a single-side ribbed duct to a smooth duct was in the range 3–4. The second assumption was that the additional pressure drop caused by the step change from a smooth to either a ribbed surface or to a rough surface was small when compared to the pressure drop across those surfaces and could
be neglected. It was justified since the step heights were small (6 mm for both the ribbed and 4 mm for the three-dimensional surfaces) when compared to the duct diameter in both cases. In addition, there are about 30 repeated roughness elements between the two pitot tubes, so that the pressure loss caused by a single step can be ignored.

The friction velocity for the duct surface roughened with regular arrays of uniform elements can be calculated from the following expression (Chamberlain, 1966; Sehmel, 1970):

\[ u_* = \sqrt{\frac{\tau_{1R}}{\rho}}, \]  

(5)

where \( \tau_{1R} \) is the wall shear stress for that surface and can be estimated as

\[ \tau_{1R} = \tau_{3D-3S-1R} - 0.75 \tau_{4S}, \]  

(6)

where \( \tau_{3D-3S-1R} \) is the total shear stress of the combination of three smooth duct surfaces and one roughened surface and can be calculated using Eq. (4) and with the Daisy–Weisbach formula (Streeter et al., 1998). \( \tau_{4S} \) is the total shear stress of a completely smooth duct and this had previously been evaluated as 0.005 (Lai et al., 1999). The coefficient 0.75 in Eq. (6) is attributable to the fact that there are only three smooth duct surfaces, rather than four, in the present work.

The above expression assumes that there is no shear-stress interaction between the rough and the smooth surfaces. Evidence of the minor interaction between ribbed and smooth surfaces was presented by Fujita (1978), who studied the distribution of shear stress for each wall in an experimental duct system. He varied the numbers of rough wall for different configurations and formulated an empirical expression for the friction factor which took into account the different numbers of rough and smooth surfaces. As his results showed that the interaction was not strong, it was considered reasonable to use Eq. (6) in the present work. Using this equation, a value for \( u_* \) of 0.28 m s\(^{-1}\) was obtained.

The aerosol particle deposition velocity to a surface is defined as

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

(7)

where \( J \) is the particle flux to the surface and \( C_\infty \) 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:

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

(8)

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

(9)

where \( M_{3D}, M_{\text{filter}} \) are the tracer aerosol 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 (12 × 6 mm) and not the total area available for aerosol deposition; this is the general practice adopted in heat transfer research (Rowley and Patankar, 1984) and has the advantage of enabling direct comparison of transfer coefficients for different configurations.
In calculating the aerosol deposition velocity, minor experimental errors of the order of 0.5% arose in the measurement of $t$ and $Q$ but the principal error sources, both of the order of 10%, arose in the measurement of $M_{\text{perspex}}$ and $M_{\text{filter}}$. The overall estimated uncertainty (using the method of Kline and McClintock (1953)) for the deposition velocity was less than 14% in all cases.

6. Results and discussion

Figure 5 shows the deposition velocity, for four particle sizes (mass medium aerodynamic diameter), on arrays of uniform elements in both the parallel and perpendicular orientation schemes. Results for the smooth and two-dimensional ribbed duct surfaces (Lai et al., 1999) are also shown for comparison. In addition, the wind-tunnel data of Sehmel (1970), which spans a comparable range of particle relaxation times, is also shown. It can be clearly seen that the presence of the three-dimensional roughened surface results in a higher aerosol deposition velocity than in the case of the ribbed surfaces, particularly for submicrometer particles. As expected in the particle size range studied, the aerosol deposition velocity is seen to increase with particle size.

Figure 6 presents the same results as shown in Fig. 5, but in another format, i.e. in this figure, the deposition velocity values are normalized with respect to those measured on the smooth duct surface. The ratio of deposition velocities on rough and smooth surfaces is seen to be as high as 20 for the 0.7 μm particles, with a minimum value occurring in the particle size range 4–5 μm.

Fig. 5. Deposition velocity for the two orientations with respect to the airflow, and compared with those measured on smooth and ribbed surfaces. The aerodynamic particle sizes measured were 0.7, 2.5, 4.5 and 7.1 μm. The data points were smoothed by spline function. Note: The data points within each group represent the same particle size and have been off-set to improve clarity.
The results shown in Fig. 5 indicate that higher deposition velocities were calculated for all particle sizes in the parallel orientation scheme than in the perpendicular scheme. The difference in deposition velocity for the two orientations and for individual particle sizes is highlighted in Fig. 7. In this figure, the individual deposition velocities for the perpendicular scheme are given the value 100% and the deposition velocities for the parallel scheme are then normalized with respect to these values. The reason for this representation of results is to determine the degree to which inertial impaction of aerosol on the roughness elements influences the calculated deposition velocities. The Stokes number, $St$ can be used to characterize the impaction effect on the frontal surfaces of the roughness elements. $St$ is defined as

$$St = \frac{d^2 \rho_p U}{18 \eta D},$$

where $d$ is the particle diameter, $\rho_p$ is the particle density, $\eta$ is the absolute fluid viscosity and $D$ is the characteristic obstruction height which in the present case, is equal to the height of the roughness elements, 2 mm. Figure 8 shows the observed linear variation in the percentage by which deposition velocity in the perpendicular scheme is exceeded by that in the parallel scheme with respect to Stokes number. Although the parallel scheme provides twice as much frontal deposition area as the perpendicular scheme it can be inferred from Fig. 7 that the maximum increment (and this occurs for the 7.1 $\mu$m particles) is only 33% and it may therefore be concluded that impaction is not the controlling deposition mechanism.

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.

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**Fig. 6.** Ratio of deposition velocity for the two orientations to the smooth surfaces. Results for the ribbed surfaces are also shown for comparison. The aerodynamic particle sizes measured were 0.7, 2.5, 4.5 and 7.1 $\mu$m. The data points were smoothed by spline function. Note: The data points within each group represent the same particle size and have been off-set to improve clarity.
Fig. 7. Percentage of deposition velocity increment in the parallel orientation, with respect to the perpendicular orientation scheme.

Fig. 8. Percentage of the deposition velocity increment, plotted against Stokes number. The line was calculated by least-squares fit of the data points.

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 in the paper, for a developed channel flow it is well known that the longitudinal velocity gradient is very steep inside the viscous layer ($y^+ \sim 5$), decreasing in the buffer and turbulent core region and becoming zero in the centerline. Since $Sc \gg 1$ for particles, 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 (Lai and Nazaroff, 2000) that the dimensionless concentration boundary thickness (which is 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. Although that work 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 (Dawson and Trass, 1972; Kozlu et al., 1992).

If this thin layer can be completely destroyed or at least made thinner, the transportation progress can be greatly enhanced. Dawson and Trass (1972) postulated a flow pattern near a rough wall and indicated that the viscous sublayer is relatively thin at the peak of roughness (Fig. 9). In the present work, the roughness elements have a protrusion height of only 2 mm and the calculated dimensionless roughness height is only 37 and is 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.

In some applications, the pressure drop penalty associated with the use of roughness elements as aerosol deposition enhancers may compromise their overall effectiveness (e.g. in electrostatic precipitators). In order to maximize the particle deposition enhancement but minimize the pressure drop penalty, the results of the present work indicate that the height of roughness element should be submerged in or closest to the viscous sublayer.
7. Conclusions and remarks

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

Generally, it was observed that the three-dimensional roughness elements which were employed enhanced particle deposition to a greater degree than the two-dimensional ribbed surface used in the same channel in an earlier investigation (Lai et al., 1999). 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. Compared with a smooth surface, the aerosol deposition enhancement level on the roughness elements varies from 6 to 18.

The parallel orientation of the roughness elements, with respect to the airflow direction in the duct, results in a higher aerosol deposition velocity than that which occurs with the perpendicular orientation. Although the frontal deposition area in the parallel arrangement is twice as high as in the perpendicular case aerosol deposition velocity in the parallel arrangements only exceeds that in the perpendicular arrangement by a maximum of 33%. This result implies that particle impaction does not strongly influence aerosol deposition in this case and this is thought to be due to the low flow velocity associated with the sublayer and buffer layer.

For the regular arrays of uniform elements studied in this work, it is concluded that their heights are submerged, or at least close to the buffer boundary and therefore little drag force is expected. In industrial devices where energy conservation is a consideration, the results indicate that the use of these types of three-dimensional surfaces may be an effective means for enhancing particle deposition. Conversely, it can be concluded that the use of small three-dimensional elements in a more turbulent flow may result in a reduction in aerosol deposition, which may be desirable in some applications.

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