

Airborne particle deposition in cleanrooms: Relationship between deposition rate and airborne concentration

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Abstract

This article is the second of a series that discusses the deposition of airborne particles onto cleanroom surfaces. It investigates the relationship between the airborne concentration of a range of cumulative sizes of particles and the particle deposition rate (PDR) onto cleanroom surfaces, through knowledge of the deposition velocity of particles in air. The deposition velocity of a range of cumulative particle sizes was obtained by means of experiments, theoretical calculations, and literature search and the influence of a number of variables found in cleanrooms on the deposition velocity was investigated. The use of the deposition velocity to calculate the amount of deposition on cleanroom surfaces, such as manufactured products, is discussed, along with its use in deciding the required ISO 14644-1 class of cleanroom; these subjects will be discussed in more depth in the final article of this series.

Introduction

The deposition of airborne particles onto cleanroom surfaces has been investigated by Whyte, Agricola and Derks (2015). A review was made of the scientific literature, which showed that the airborne deposition mechanisms in cleanrooms were likely to be gravitational, turbulent deposition, Brownian diffusion, and electrostatic attraction. An experimental investigation showed that for particles $\geq 10\mu\text{m}$, gravitational settling accounted for over 80% of surface deposition.

Cleanrooms are classified according to ISO 14644-1 by their cumulative airborne particle concentration. The cumulative size includes all particles equal to, and above, a given size, rather than one discrete size or range of sizes. However, knowledge of the airborne concentration will fail to give information

on how many particles deposit from air and contaminate a product, and to obtain this, the particle deposition rate (PDR) is required. The PDR is the number of particles of a specific size that deposit onto a standard surface area such as a dm^2 or m^2 , in a standard time such as an hour or second. The units used in this article are dm^2 per hour, which give results close to the actual results obtained in a cleanroom. To specify the PDR in terms of the particle size, the notation 'PDR_D' is used, where 'D' is the particle size.

If the PDR is known, then the number of particles deposited from air onto a surface, such as a manufactured product, can be calculated as follows:

Equation 1

Number of particles deposited = PDR * a * t

Where, a = area of exposed surface, and t = time the surface is exposed

It is assumed in Equation 1 that the surface area exposed to particle deposition is horizontal. If the surface slopes at an angle of x° to the horizontal, and the deposition mechanism is gravitational, an 'effective area' should be used. This is obtained by multiplying the actual surface area by $\cos x^\circ$ (Whyte et al, 1982).

PDRs can be obtained by instruments designed for the purpose (Agricola, 2014, 2015) but these are not as common in cleanrooms as airborne particle counters. Airborne particle counters are used to measure and count each airborne particle from the amount of light it reflects as it passes through a light beam, and then ascertain the airborne concentration of given sizes. These instruments are known in this article as airborne particle counters. It would be useful if the PDR could be calculated from the airborne concentration obtained from these instruments.

If an acceptable rate of surface contamination by airborne deposition is defined, it would be a considerable advantage if the ISO 14644-1 class limit of particles/ m^3 , could be determined to ensure the defined amount of surface contamination is not exceeded. If the defined rate of surface contamination of a product is given in terms of the PDR, and the deposition velocity known, the required airborne concentration can be obtained by use of Equation 2. If the required airborne particle concentration is known, then the cleanroom's air supply rate can be determined (Whyte et al, 2014).

The relationship between the PDR, airborne concentration of particles, and deposition velocity is as follows:

Equation 2

PDR = C_D * V_D

Where, C_D = airborne particle concentration of particles of a size D μm , and V_D = deposition velocity of particles of a size, D μm

The deposition velocity (V_D) is the velocity of a discrete, or cumulative, size of particle approaching a surface. This velocity can be caused by various deposition forces such as air turbulence and electrostatics but it has been shown in many situations in cleanrooms that the deposition velocity is caused by gravity (Whyte, Agricola and Derks, 2015).

Deposition velocity of particles

Whyte, Agricola and Derks (2015) have shown that over 80% of airborne particles $\geq 10\mu\text{m}$ are deposited in a cleanroom by gravitational settling, and a review of the scientific literature shows that gravitational settling will be a predominant mechanism down to about $5\mu\text{m}$, and an important one down to about $0.5\mu\text{m}$.

Knowing that gravity is the force that causes most of the particles $\geq 5\mu\text{m}$ in cleanroom air to settle onto surfaces, the deposition velocity of discrete sizes of particles, as they settle through the air, can be calculated by Stokes settling equation (Hinds, 1999). This is correct in the range of particle diameters from about $1.5\mu\text{m}$ to $75\mu\text{m}$, where Equation 3 is accurate to better than 10%.

Equation 3

$$D_v = \frac{\rho_p \cdot g \cdot d^2}{18 \cdot \eta}$$

Where, D_v is the deposition velocity (m/s), ρ_p = density of particle (kg/m^3), g = acceleration due to gravity ($9.81 \text{ m}/\text{s}^2$), d = particle diameter (m) and μ = viscosity of air ($1.18 \times 10^{-5} \text{ kg}/\text{m}\cdot\text{s}$)

For particles smaller than about $1.5\mu\text{m}$, the result obtained from Equation 3 will be more accurate if the result is multiplied by a slip correction factor, but this is not necessary in this article as the particle sizes that are considered are $\geq 5\mu\text{m}$. However, when particles are larger than about $75\mu\text{m}$, the deposition velocity can be more accurately calculated by use of Equation 4.

Equation 4

$$D_v = \left(\frac{\eta}{\rho_a d} \right) \exp(-3.070 + 0.9935 \cdot J - 0.0178 \cdot J^2)$$

Where J is obtained as follows:

$$J = \ln\left(\frac{4 \cdot \rho_p \cdot \rho_a \cdot d^3 \cdot g}{3 \eta^2}\right)$$

and, ρ_a is the density of air at 20°C ($1.2 \text{ kg}/\text{m}^3$)

Naturally-occurring particles exist in cleanroom air in a variety of shapes and densities that affect their deposition velocity. The shape and the density of particles in room air are relatively unknown, and it is convenient and conventional to consider particles, especially in situations where surface deposition is considered, as an equivalent aerodynamic diameter. This is the diameter of a sphere with a density of $1000 \text{ kg}/\text{m}^3$ that has the same aerodynamic properties, such as gravitation settling through the air, as the particle being considered. If the density of the particles is known, then the particle can be described by Stokes diameter, which is the equivalent diameter of a sphere with

the same aerodynamic properties and density as the particle being considered.

The main source of particles in a typical cleanroom is personnel, who disperse particles from their skin and garments. The density of skin particles is $1100 \text{ kg}/\text{m}^3$ (Leider and Buncke, 1954), and polyester used in cleanroom garments has a density of $1380 \text{ kg}/\text{m}^3$; it is therefore reasonable to assume a density of $1200 \text{ kg}/\text{m}^3$ for airborne particles found in cleanrooms.

It should be noted that the deposition velocities of particles discussed in this section are for discrete particle sizes. However, particle concentrations are usually measured in a cleanroom as cumulative sizes, and a method for calculating the deposition velocity of cumulative sizes is given later in this paper.

An alternative method of calculating the deposition velocity to Stokes settling equation is by experimental measurements. If the airborne concentration and PDR of particles are measured at the same location, then the deposition velocity can be calculated by Equation 5. This experimental method is described later in this paper.

Equation 5

$$\text{Deposition velocity (m/s)} = \frac{\text{PDR (no./m}^2\text{/s)}}{\text{particle concentration (no./m}^3\text{)}}$$

The value of the deposition velocity may be influenced by a) the cleanroom's air supply rate and turbulent intensity of the air, and b) the size distribution of the particles that will deposit on surfaces. The effect of these variables is investigated in this article.

Previous research into the relationship between airborne particle concentration and PDR

The relationship between airborne concentration of particles $\geq 5\mu\text{m}$ and PDR was obtained from a study of a wide variety of cleanrooms that was reported by Hamberg (1982). The following relationship, which has been transformed for use with SI units, was obtained:

Equation 6

$$\text{PDR}_{\geq 5\mu\text{m}} = 81.2 \cdot C^{0.773}$$

Where, $\text{PDR}_{\geq 5\mu\text{m}}$ = number of particles $\geq 5\mu\text{m}/\text{m}^2/\text{hr}$, and C = concentration of airborne particles $\geq 5\mu\text{m}/\text{m}^3$

Equation 6 predicts that there will be more particles deposited at lower particle concentrations than expected by the drop in the airborne concentration. The magnitude of this effect can be calculated by considering two cleanrooms with different airborne particle concentrations. The first cleanroom is an ISO Class 8 with a class limit of particles $\geq 5\mu\text{m}$ of $29,300/\text{m}^3$, and the PDR can be calculated by use of Equation 6 to be $230,380 / \text{m}^2/\text{hr}$. The second cleanroom is an ISO Class 6 with a class limit of particles $\geq 5\mu\text{m}$ of $293/\text{m}^3$, and the PDR calculated to be $6,535 / \text{m}^2/\text{hr}$. Therefore, a 100-fold reduction in the airborne particle concentration caused by a reduction in air cleanliness from ISO Class 8 to ISO Class 6, gives a 35-fold reduction in the PDR. There are therefore approximately 3 times more particles deposited than expected from the reduction in airborne particle concentration.

Parasuraman et al (2012) carried out experiments in a cleanroom and obtained a similar equation to Hamberg, and when the time units in his equation are changed to hours the following equation is obtained:

Equation 7

$$\text{PDR}_{\geq 5\mu\text{m}} = 158.7 \cdot C^{0.767}$$

Where, $\text{PDR}_{\geq 5\mu\text{m}}$ = number of particles $\geq 5\mu\text{m}/\text{m}^2/\text{hr}$, and C = concentration of airborne of particles $\geq 5\mu\text{m}/\text{m}^3$

If the same classes of cleanrooms are again considered (ISO Class 8 and 6), a 100-fold reduction in the air concentration gives a reduction in the PDR of 34-fold, and 3 times more particle deposition than anticipated by the airborne particle concentration. This strongly supports Hamberg's results that the PDR is dependent on the airborne particle concentration,

Hamberg was able to study a range of cleanrooms that included non-unidirectional and unidirectional types. His results showed that if air cleanliness changed from an ISO Class 8 cleanroom to ISO Class 7, the particle deposition increased by about 1.7 times more than expected from the reduction of airborne particle concentration, and when changed to an ISO Class 6 and ISO Class 5, it increased by about 3 and 5 times, respectively.

Hamberg (1982) suggested that the reason for the disproportionate increase in deposition rates was that lower airborne concentrations were associated with higher air supply rates and he wrote that ‘small particles ($<10\mu\text{m}$) can be carried out of the cleanroom before they have a chance to settle and, consequently, fewer particles will settle out as the purging rates increase’. However, Hamberg did not consider that the turbulent intensity of the air would increase with supply rate and cause more deposition, and this may be another explanation.

The overall average concentration of particles $\geq 5\mu\text{m}$ found in our experiments, and shown in Table 1, was $19,514/\text{m}^3$. Using Hamburg’s equation (Equation 6), and then Equation 2, the deposition velocity of particles $\geq 5\mu\text{m}$ can be calculated to be 0.24 cm/s . Similarly, Parasuraman’s results gave a deposition velocity of 0.44 cm/s . However these velocities apply to an ISO Class 8 cleanroom and should be increased by 1.7-fold if applied to an ISO Class 7 cleanroom, 3-fold if applied to an ISO Class 6 cleanroom, and 5-fold if applied to an ISO Class 5.

Carr et al (1994) reported that the deposition velocity of a cumulative particle size of $\geq 0.3\mu\text{m}$, during manufacture in a semiconductor cleanroom, was 0.003 cm/s .

Experimental equipment and methodology

Experimental cleanroom

The cleanroom used in these experiments was a non-unidirectional airflow type with a floor area of 6 m long and 4.2 m wide, and a room volume of 72.9 m^3 . It had previously been used by Whyte, Agricola and Derks (2015). To elevate the airborne particle concentration in the experiments, the air supply was reduced from its normal rate to $900\text{ m}^3/\text{h}$ by switching off 6 of the 8 fan-filter units. This gave 13 air changes per hour. The fan-filter air outlets did not have air diffusers, and to assist the mixing of supply air with cleanroom air, the location of the two active fan-filter units was about one third of the length of the cleanroom, and the sampling location was two thirds.

Experiments were carried out in the following ventilation conditions:

1. 13 air changes of HEPA-filtered air per hour,

2. A ‘no ventilation’ condition where all the fan-filter units were switched off,
3. A ‘unidirectional airflow’ condition where a table fan was used in the unventilated condition to direct room air in a unidirectional manner at a velocity of 0.75 m/s to the sampling location.

During the experiments, the cleanroom was occupied by the authors of this article, who mainly sat at the end of the cleanroom where the fan-filter units and table fan was sited, and worked with their computers, talked, and occasionally walked around the room. To increase airborne dispersion, and hence the airborne particle concentration, they wore their ordinary indoor clothing.

The surface cleanliness of the floor was not measured but experience suggests that it was likely to be that of a cleaned office i.e. between SCP 6.5 and SCP 7, as defined by ISO 14644-9. Agricola (2015) reported that differences in the size distribution of deposited particles were related to the surface cleanliness of cleanrooms, with a larger proportion of particles $\geq 30\mu\text{m}$ being deposited on the surface of a dirty cleanroom than in a clean one. Our experimental cleanroom was little used and the floor only cleaned when needed and it was not cleaned before these experiments. It was, therefore, expected that the size distribution of the PDR would be similar to that found in the dirty cleanroom. However, if the size distribution found in the experimental cleanroom and shown in Figure 4 is compared with the size distributions reported by Agricola, it can be seen that it was closer to a clean cleanroom. The explanation of this difference is likely to be caused by the low level of activity during our experiments that failed to disperse particles from the cleanroom’s surfaces.

Measurement of airborne particle concentration

The concentration of airborne particles was measured by a Lighthouse Boulder particle counter, which sampled $28.3\text{ l}/\text{min}$, and counted the following sizes: $\geq 5\mu\text{m}$, $\geq 10\mu\text{m}$, $\geq 25\mu\text{m}$, $\geq 40\mu\text{m}$, $\geq 50\mu\text{m}$ and $\geq 100\mu\text{m}$. Air sampling occurred during the whole time of the experiments and was carried out in the three ventilation conditions. The measurements

were repeated and averages obtained. The particle counter was calibrated according to ISO 21501-4, which requires a high counting efficiency for any particle that enters the particle counter. However, particle deposition losses could occur in a sampling tube, and a tube was not used. The inlet nozzle is designed for isokinetic sampling in unidirectional airflow, but has an aerodynamic shape that was likely to minimise particle losses by surface deposition in non-unidirectional airflow conditions (Agarwal and Lui, 1980).

Measurement of particle deposition rates (PDR)

Glass witness plates of 12 cm diameter were cleaned and exposed in the cleanroom for approximately 90 minutes and, after exposure, the surface particles were immediately counted and sized by a PDM instrument (SAC, Netherlands). The area of the witness plate on which the particles was measured and counted was 49 cm^2 , and the PDR was reported as number of particles $/\text{dm}^2/\text{h}$. The PDM instrument measured and counted the same particle sizes as the airborne particle counter, namely, $\geq 10\mu\text{m}$; $\geq 25\mu\text{m}$; $\geq 40\mu\text{m}$; $\geq 50\mu\text{m}$ and $\geq 100\mu\text{m}$, with an accuracy of $\pm 5\mu\text{m}$. The top surface of each particle was measured and this area converted to an equivalent diameter. The measurements were repeated and an average calculated.

Experimental results

Experimental airborne particle concentrations

Given in Table 1 are the average airborne concentrations of the cumulative particle diameters in the three ventilation conditions, as well as the overall average concentrations of all three ventilation conditions. As expected, the lowest concentrations were obtained when the cleanroom was supplied with 13 air changes per hour, and the higher concentrations were obtained when the air conditioning was switched off during both the unidirectional and unventilated conditions. All airborne conditions conformed to an ISO Class 8 particle concentration limit.

To allow a comparison of the particle size distributions from different airborne particle concentrations in the three ventilation conditions, the concentration of each cumulative particle size was

calculated as a percentage of the total count of particles $\geq 5\mu\text{m}$. These percentage concentrations are shown in Figure 1.

It can be seen in Figure 1 that there is little difference between the airborne concentrations of the cumulative particle size range between 5 and $25\mu\text{m}$ in the different ventilation conditions, and this size range accounts for about 98% of the particles. For larger particles, the 13 air changes per hour had the highest percentages. It is interesting to note the change in gradient of the plots at about $40\mu\text{m}$. Many of the airborne particles in the experimental cleanroom were likely to be dispersed from people as skin cells, or fragments of skin cells. Skin cells are about $33\mu\text{m} \times 44\mu\text{m}$ in area, with a thickness of about $4\mu\text{m}$ (Mackintosh, et al, 1978). Skin cells may be dispersed as multiple cells but will more frequently fragment, and the plots may reflect this.

The overall average concentrations of airborne particle measured in all three ventilation conditions are also given in Figure 1, along with the equation that best fits these results.

Experimental PDRs and deposition velocities

Given in Table 2 are the PDRs for each ventilation condition that were obtained adjacent to where the airborne particle concentration was measured. Again, to allow comparisons between the different airborne concentrations in the different ventilation conditions, the PDRs of the range of particle sizes are given in Figure 2 as a percentage of the total number of particles $>10\mu\text{m}$. It can be seen that the plots from the three ventilation conditions were similar to the plots of the airborne particle concentrations in Figure 1, with the greatest deposition of larger particles occurring in the 13 air changes per hour condition.

Using the overall averages of the airborne particle concentrations given in Table 1 and the PDRs given in Table 2, which were measured over the same time and at the same location, the deposition velocities were calculated by means of Equation 5, and given in Table 3.

PDR and deposition velocities calculated by means of Stokes settling equation

The deposition velocities of discrete sizes of airborne particles can be calculated by Stokes settling equations (Equations

Table 1: Airborne particle concentration/ m^3

Ventilation condition	Particle diameter (μm)					
	≥ 5	≥ 10	≥ 25	≥ 40	≥ 50	≥ 100
13 air changes/hour	8403	3503	222.5	16	9.5	1.60
No ventilation	21226	7010	305.5	12	6.5	0.75
Unidirectional	28913	8016	467.5	36	23.0	2.29
Overall average of 3 conditions	19514	6176	322	21	13.0	1.55

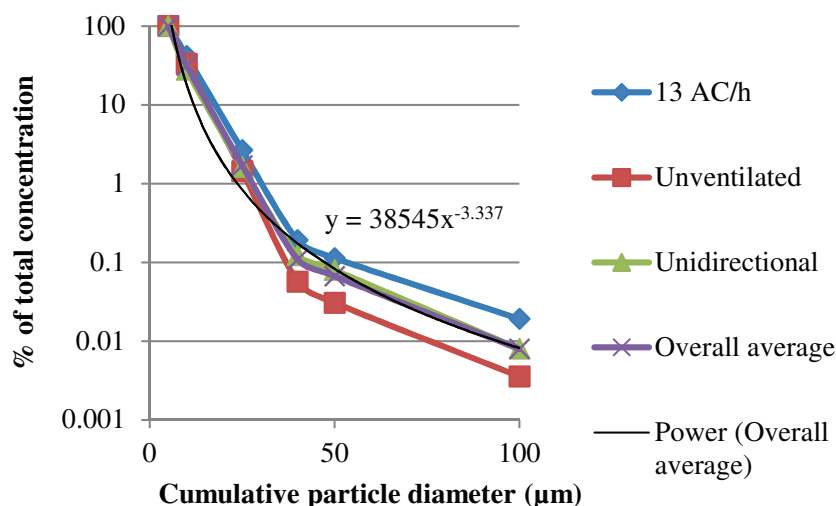


Figure 1: Airborne particle concentrations as a percentage of the total counts

Table 2: Measurements of PDRs in three ventilation conditions

Ventilation conditions	PDR (no./ dm^2/h)				
	$\geq 10\mu\text{m}$	$\geq 25\mu\text{m}$	$\geq 40\mu\text{m}$	$\geq 50\mu\text{m}$	$\geq 100\mu\text{m}$
13 air changes/ hour	612	411	138	76	16
Unventilated	875	466	120	57	9
Unidirectional	1306	849	310	162	12
Overall average	931	575	189	98	12

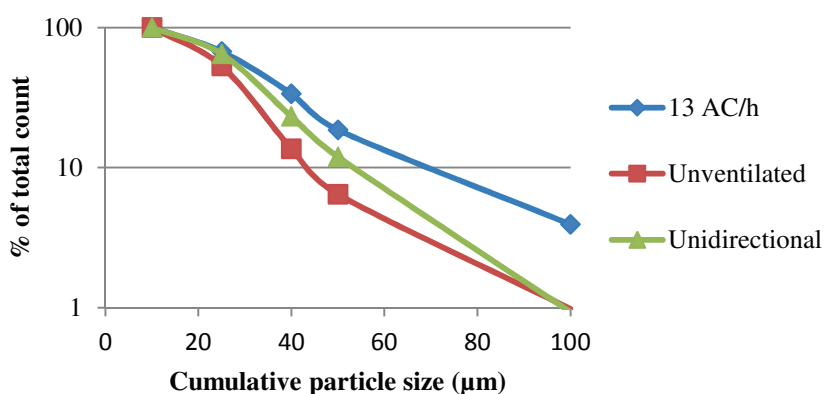


Figure 2: Percentages of PDRs of total deposition rate

Table 3: Deposition velocities (cm/s) determined experimentally in a cleanroom

Cumulative particle size	≥10µm	≥25µm	≥40µm	≥50µm	≥100µm
Deposition velocity (cm/s)	0.42	5.0	25	21	17

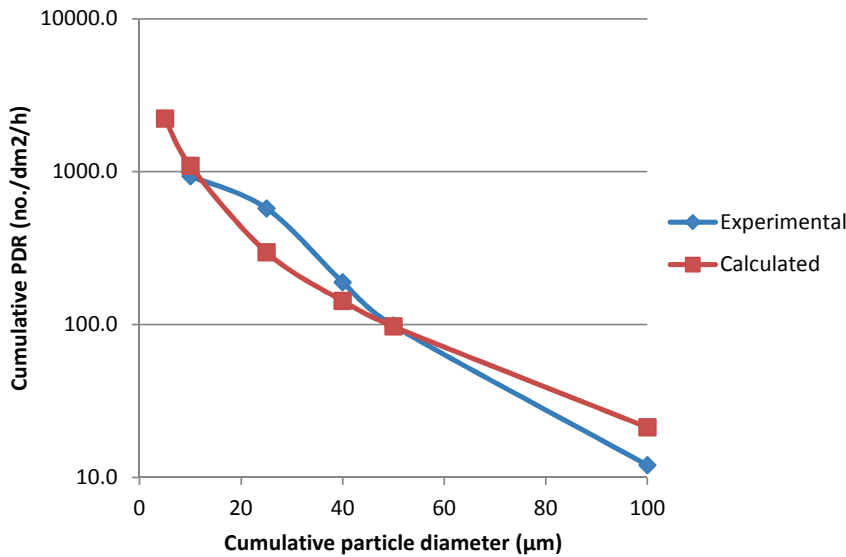


Figure 3: Experimental and calculated PDRs

Table 4: PDR and deposition velocities obtained from airborne concentrations and Stokes settling equation

Cumulative diameter (≥µm)	Experimental airborne particle conc./m ³	PDR calculated by Stokes equation (no/dm ² /h)	Deposition velocity (cm/s)
5	19514	2226	0.31
10	6176	1093	0.49
25	322	297	2.56
40	21	142	18.8
50	13	97	20.7
100	1.6	21	29.5

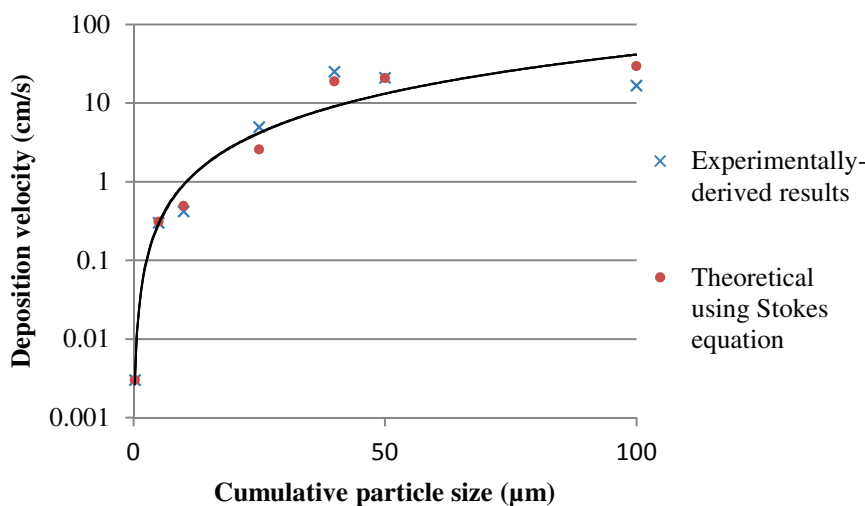


Figure 4: Deposition velocities obtained from experimental and calculated results

3 and 4). However, deposition velocities were required of cumulative sizes and these can be obtained by a method outlined by Hamberg (1982).

Previously shown in Figure 1 is a plot of the overall averages of the airborne concentrations of the cumulative particle sizes given as a percentage of the total number of particles ≥5µm. Also given is the best-fit equation of this plot that can be used to calculate the proportion of any cumulative size of particle, and these proportions were calculated in steps of 1µm, from 5µm to 200µm. An upper limit of 200 µm was chosen, as it can be seen in Figure 1 this would include most of the airborne particles found in a cleanroom i.e. 99.99%. By subtracting the proportions of adjacent cumulative particle sizes, the proportion of discrete particle diameters, in steps of 1µm, was obtained. Using Stokes settling equations, and assuming a particle density of 1200kg/m³, the deposition velocity was calculated for each discrete particle size. For particles between 5 and 75µm, Stokes settling Equation 3 was used, and for particles above 75µm, Equation 4 was used.

The PDR was calculated for each discrete particle size by multiplying the airborne concentration with its associated deposition velocity. The PDR of particles, greater and equal to, 5, 10, 25, 40, 50 and 100µm was then obtained by summing the PDRs of all discrete sizes greater than the size being considered. These PDRs are given in Table 4, and plotted in Figure 3. Also plotted in Figure 3 are the PDRs measured in the cleanroom, and it can be seen that the experimental and theoretical results are similar, although the PDR of the smaller particles measured in the cleanroom levelled off quicker than the theoretical results. Finally, the deposition velocities of the cumulative particle size were calculated from the airborne particle concentrations and their associated PDR, and use of Equation 2. These velocities are given in the final column of Table 4.

Combined deposition velocities

Plotted in Figure 4 are the settling velocities of a range of cumulative particle sizes obtained from the following sources:

- The airborne particle concentrations and PDRs measured experimentally in a cleanroom, and reported in Table 3.

- Use of Stokes settling equation, and reported in Table 4.
- The deposition velocity given by Carr (1994) for particles $\geq 0.3\mu\text{m}$.
- The deposition velocity of particles $\geq 5\mu\text{m}$ obtained from use of Stokes settling equation was 0.33 cm/s. The deposition velocity calculated from Hamberg's equation (Equation 6) was 0.24cm/s, and Parasuraman's equation (Equation 7) gave a value of 0.44cm/s. These three deposition velocities were similar, and an average result of 0.30 cm/s was used.

The best-fit lines for both the experimental and theoretical results are shown in Figure 4. These curves are almost identical, and the best-fit equation of the combined results is as follows:

Equation 8

$$D_v = 0.0202 * d^{1.656}$$

Using Equation 8, the deposition velocities were calculated for a range of cumulative particle diameters and given in Table 5.

Discussion and conclusions

Cleanrooms are classified according to the concentration of airborne particles. However, knowing the concentration of airborne particles does not allow the contamination rate of manufactured products to be predicted. What is required is the PDR. Instruments have been available for some time to measure the PDR onto cleanroom surfaces such as silicon wafers, but it is only recently that relatively inexpensive and portable instruments have become available (Agricola, 2014, 2015). If the PDR is known, then the product contamination rate can be calculated from knowledge of the area of product open to airborne contamination, and the time exposed. This method will be discussed more fully in our third and final article.

At present, the instrument most commonly used to ascertain cleanroom cleanliness is an airborne particle counter, which uses light-scattering of single particles to determine their size and airborne concentration. However, if the deposition velocity is also known, the PDR can be calculated by means of

Equation 2 and the likely amount of product contamination then ascertained by Equation 1. Similarly, if the acceptable deposition rate of particles onto a product is known, the required air concentration to achieve this can be calculated by means of the deposition velocity, and knowing this airborne concentration, the air supply rate can be calculated (Whyte et al, 2014). The airborne concentration of particles is normally measured in cleanrooms as cumulative counts and, therefore, the deposition velocities are required for a range of cumulative particle sizes. These have previously been unavailable, but were obtained in this investigation.

A range of deposition velocities of cumulative particle sizes were calculated from observations of airborne particle concentrations and PDRs in an experimental cleanroom, and use of Equation 5. Deposition velocities were also calculated from airborne particle concentrations and Stokes settling equations (Equations 3 and 4) and these results conform well to the experimental results. In addition, the deposition velocity obtained by Carr et al (1994) for particles $\geq 0.3\mu\text{m}$ was included, as was additional information from Hamberg (1982) and Parasuraman et al (2004) on the deposition velocity of particles $\geq 5\mu\text{m}$. All these results fit well into the relationship plotted in Figure 4, and the resulting equation of the plot was used to obtain a range of cumulative deposition velocities given in Table 5. The accuracy of the deposition velocities may be influenced by several variables, and these were investigated.

Hamberg (1982) obtained an equation (Equation 6), for calculating the PDR of particles $\geq 5\mu\text{m}$ from the airborne particle concentration. He found a disproportionately-higher PDR was associated with lower concentrations of airborne particle. This was confirmed by Parasuraman et al (2008). Results have also been published by Lidwell et al (1983) about the deposition velocity of microbe-carrying particles (MCPs) found during their study of airborne contamination in operating theatres. Lidwell's results showed that the deposition velocity of MCPs in non-

unidirectional airflow operating theatres, with about 20 air changes per hour, was about 0.33cm/s, and in unidirectional airflow systems with low concentrations of airborne MCPs, it was about 1.33cm/s. Using Stokes settling equation (Equation 3), the average aerodynamic size can be calculated to be 10.5 μm in non-unidirectional airflow and 21 μm in unidirectional airflow.

Hamberg suggested the reason for the disproportional amount of deposition is that lower particle concentrations are associated with higher air supply rates, where smaller particles are quickly swept from the cleanroom with little time to deposit. However, the larger particles will still deposit and the disproportionate effect increases as the average residence time of the air reduces. Our experimental results, shown in Figures 1 and 2, support the suggestion that a higher proportion of larger particles are deposited in the ventilated cleanroom than in the unventilated cleanroom. An additional explanation of the disproportional increase in particle deposition could be the higher turbulent intensities associated with the greater air supply. However, a previous article (Whyte, Agricola and Derks, 2015) showed that turbulent intensity did not have a large effect on particle deposition in cleanrooms and, perhaps, accounted for about 10% of macro particle deposition.

The cumulative deposition velocities given in Table 5 (with the exception of particles $\geq 0.3\mu\text{m}$) were obtained in an ISO Class 8 cleanroom and can be applied to this class of cleanroom. However, if the cleanroom is an ISO Class 7 cleanroom, both Hamberg's and Parasuraman's equations show that the PDR and deposition velocity were likely to be 1.7 times greater, and in an ISO Class 6 and 5 cleanrooms they would be 3 and 5 times greater, respectively. Hamberg's and Parasuraman's results were for particles $\geq 5\mu\text{m}$, and Lidwell's results were for an average size of MCPs in the range of between 10 μm to 21 μm , and it is reasonable to assume that the disproportionate increase in deposition will occur over this range of cumulative particle sizes. However, particles in the size region of $\geq 0.3\mu\text{m}$ and $\geq 0.5\mu\text{m}$

Table 5: Deposition velocities of a range of cumulative particle diameters

Cumulative particle diameter	$\geq 0.3\mu\text{m}$	$\geq 0.5\mu\text{m}$	$\geq 5\mu\text{m}$	$\geq 10\mu\text{m}$	$\geq 25\mu\text{m}$	$\geq 40\mu\text{m}$	$\geq 50\mu\text{m}$	$\geq 100\mu\text{m}$
Deposition velocity (cm/s)	0.0028	0.0064	0.29	0.91	4.2	9.1	13	41

should act similarly to a gas, and surface deposition will be little affected by changes to the air supply volume and turbulence, and the one deposition velocity may be applied to a range of cleanliness classes.

The concentration of airborne particles was measured as a cumulative size. Variations in the proportion of the particle sizes above the cumulative particle size could cause a change to the PDR and, therefore, the calculated deposition velocity. Agricola (2015) reported that the size distribution of particles deposited onto surfaces differs between cleanrooms that were 'at rest' and 'in operation'. However, the objective of this investigation was to determine deposition velocities so that the airborne contamination of products could be calculated, and only operational conditions should therefore be considered. Agricola (2015) also reported differences in the size distribution of deposited particles were related to the surface cleanliness of cleanrooms, with a larger proportion of particles $\geq 30\mu\text{m}$ being deposited in a dirty cleanroom than in a clean one. Our experimental cleanroom was considered to be 'dirty' but the size distribution of the PDR was similar to that found in a 'clean' cleanroom by Agricola (2015). The explanation of this is likely to be the low level of activity during our experiments that failed to disperse particles from surfaces.

The cumulative deposition velocities determined in this investigation can be used to calculate the PDR from knowledge of the airborne particle concentration. However, to obtain the best results some restrictions should be applied. The calculations should only be applied to operational conditions in a cleanroom. Also, to minimise the effect of the change in the size distribution caused by variations in surface cleanliness and activity, the use of PDRs for particles above about $30\mu\text{m}$ is best avoided. The deposition velocities in Table 5 can be directly applied to an ISO Class 8 room, but for particles $\geq 5\mu\text{m}$ they should be increased by 1.7-fold if applied to an ISO Class 7 cleanroom, 3-fold if applied to an ISO Class 6 cleanroom, and 5-fold if applied to an ISO Class 5. The deposition velocity of particles $\geq 0.3\mu\text{m}$ or $\geq 0.5\mu\text{m}$ can be applied to a range of cleanroom classes.

Using the suggestions given in the above paragraph, the particle deposition on surfaces such as manufactured products can be calculated using the deposition velocities obtained by this investigation. However, owing to the variables discussed and investigated in this article, it should not be expected that the deposition velocities will accurately calculate the PDR, and further research is required to increase the accuracy. To calculate the amount of surface contamination from knowledge of the airborne particle concentration is a considerable step forward from the present situation where the amount of airborne contamination of products is not calculated. Also, the choice of the ISO class of cleanroom required for a given type of manufacturing is based, at present, on an informed guess that often leads to cleanrooms being over-supplied with filtered air, or occasionally, with insufficient air. The correct airborne cleanliness class for an acceptable amount of airborne product contamination can be calculated by use of the deposition velocity. How these calculations can be carried out is discussed in the next and final article in this series.

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Biographical notes for the authors are given in CACR24 (October 2015)