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Ventilation effectiveness in cleanrooms and its relation to decay rate, recovery rate, and air change rate

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Non-unidirectional airflow cleanrooms are supplied with filtered air to minimise the contamination of a product or process by airborne contamination. The effectiveness of the ventilation system in providing the required type of airflow in the cleanroom that will minimise airborne contamination can be assessed by measuring ventilation effectiveness indexes. This article provides information on what ventilation effectiveness indexes are suitable for cleanrooms, and how they can be obtained by test methods in common use in cleanrooms. Three methods of measuring ventilation effectiveness are discussed, namely, the Contamination Removal Effectiveness (CRE) index, the Air Change Effectiveness (ACE) index and the Performance Index (PI), and it was considered that the ACE index and PI were the most suitable for use in cleanrooms.

The decay rate and recovery rate of airborne contamination in relation to the air change rate in non-unidirectional cleanrooms is also considered, and it is demonstrated that when measured at the same location, the three rates are identical. Also considered is the measurement of these rates in cleanrooms and how they can be used to obtain the ACE index.

Key words: Ventilation effectiveness, cleanrooms, decay rate, recovery rate, air change rate.

Introduction

Airborne cleanliness of a non-unidirectional airflow (non-UDAF) cleanroom is dependent on the rate that the air supply volume of filtered air is supplied to the cleanroom. However, if there is unsatisfactory airflow within the cleanroom, then critical locations may receive less clean air supply, or there may be greater transfer of contaminants from sources, and these may lead to increased airborne contamination.

The effectiveness of ventilation in ensuring that critical locations in the cleanroom do not have higher concentrations of airborne contaminants than average can be assessed by ventilation effectiveness (VE) indexes. Although information on VE indexes is readily available for ordinary mechanically ventilated rooms, such as offices[1], information is limited on suitable VE indexes for use with cleanrooms, and the methods to obtain their numerical values.

Knowledge of the decay rate of airborne particles in non-UDAF cleanrooms is required to test the ability of a cleanroom to recover from a temporary increase in airborne contamination, and a recovery test is described in International Organization for Standardization (ISO) 14644-3: 2005 Test Methods[2]. In cleanrooms, the decay rate of airborne contaminants is often called ‘recovery rate’, and both terms are interchangeable. It has also been shown that these terms are the same as the air change rate at the location where they are measured[3,4]. The meaning and interconnection of these three terms has been discussed in these previous articles but some additional clarification is required, as well as further information about their use in cleanrooms to obtain and calculate a VE index.

Ventilation effectiveness

Ventilation effectiveness in cleanrooms

To obtain a low concentration of airborne contaminants, non-UDAF cleanrooms are supplied with large quantities of filtered air that mix and dilute airborne contaminants, and remove contaminants through the air exhausts. This should be done efficiently, but there may be locations in a cleanroom

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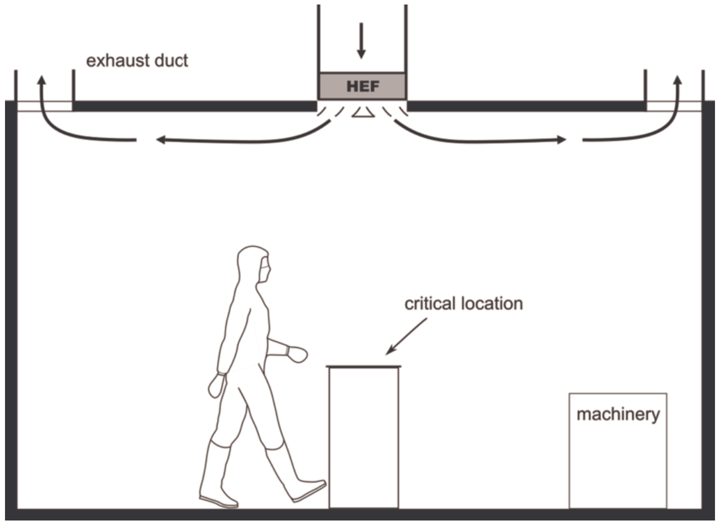

Figure 1. Short-circuiting of supply air in a non-UDAF cleanroom; HEF: high-efficiency filter.

Another example is where air is supplied horizontally by a high-level linear grille. In that situation, some of the air supply is likely to pass across the ceiling, down the opposite wall, over the floor, and up the wall, to be entrained in the air supply. This airflow pattern is likely to result in the air in the centre of the cleanroom being relatively stagnant, with higher than average concentrations of airborne contaminants that may contaminate any product or process located in that area.

In ordinary mechanically ventilated rooms, such as offices, a concern is whether there is sufficient fresh air for the occupants to breathe, although the removal of undesirable contaminants may also be required. In a cleanroom, areas of concern are how efficiently filtered air supply reaches locations where the product, or process, is exposed to airborne contamination, and how efficiently airborne contaminants are removed from a source, or sources, and prevented from reaching critical locations.

where clean air does not penetrate well because of (a) the position of air inlets; (b) characteristics of the air inlet diffusers; (c) temperature differences between supply and room air; (d) placement of exhausts; (e) obstructions to airflow; and (f) air rising from heat sources. These variables can influence the airflow patterns within the cleanroom and reduce the amount of clean air that reaches critical locations[4,5].

An example of the lack of clean air being provided at critical locations is illustrated in **Figure 1**, where filtered air is supplied through an air diffuser in a ceiling inlet, and also extracted at high level. This is not a typical cleanroom design but a design used in ordinary mechanically ventilated rooms to avoid the need to run ducts down to the low-level exhausts. However, it is useful in illustrating poor ventilation effectiveness. In this situation, inlet air will short-circuit to the exhausts, especially when the air supply is warmer and more buoyant than room air, and this will result in less clean air being available at critical locations at working height.

If VE indexes are available from the literature, previous similar building projects, or computational fluid dynamics (CFD) analysis, then they can be used during the design of new or modified cleanrooms to ensure that critical locations do not have higher than average concentrations of airborne contaminants. Should higher concentrations be likely, modifications should be made to the airflow design within the cleanroom, or the air supply rate increased to compensate for the conditions[6]. In addition, measuring the value of a VE index in newly installed, or modified, cleanrooms will ensure that no airborne contamination problems are likely to occur at critical locations because of inadequate supplies of clean air, or ineffective removal of contaminants.

Types of VE indexes

Information about VE indexes is available in the REHVA (Federation of European Heating and Air-conditioning Associations) Guidelines No 2: Ventilation Effectiveness[1] where it is considered that VE indexes can be divided into two main categories.

1. Contamination Removal Effectiveness (CRE) indexes.
2. Air Change Effectiveness (ACE) indexes.

The REHVA Guidelines consider that if the most important function of the ventilation within a room is to remove particle or chemical contaminants generated by a known static source, the CRE index should be used. In all other cases, where the object is to provide as much clean air as possible to critical locations, the ACE index should be used.

A third type of VE index that has properties that are useful in cleanrooms is the Performance Index (PI), but this index is not considered in the REHVA Guidelines No 2. These three types of VE indexes are now discussed.

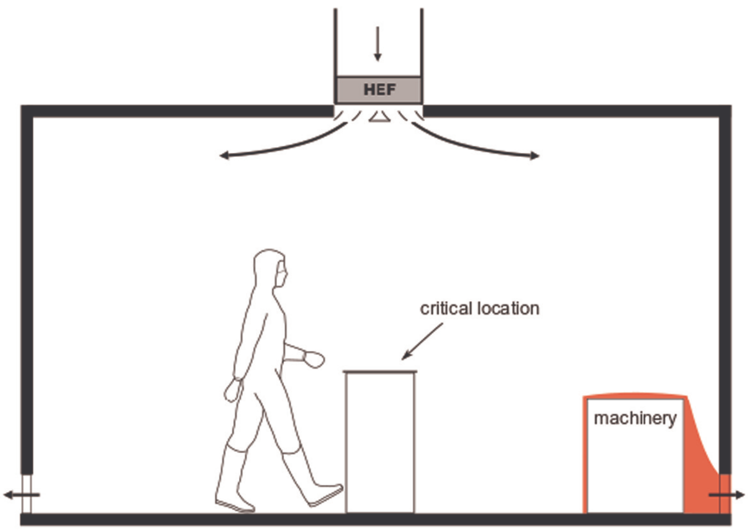

Figure 2. Effective removal of contaminants from machinery and high CRE index; ■ : airborne contamination.

Contamination Removal Effectiveness (CRE) index

The CRE index measures the effectiveness of the removal of airborne contaminants emitted by a static source. Shown in **Figure 2** is a non-UDAF cleanroom containing a machine that emits large amounts of airborne particles. To minimise the spread of the airborne contaminants round the cleanroom, the design of the cleanroom should ensure that the machine is placed close to an air exhaust in the manner shown in the figure, or adjacent to an exhaust hood. The most suitable position of the machine, in relation to its operational effectiveness and the required air extract rate, can be obtained by measuring the CRE index.

As far as the authors are aware, there is no national or international standard that defines the CRE index and gives a method for measuring it. However, REHVA Guidelines No 2 gives a method where a tracer gas like SH_6 or N_2O is introduced at the source of contamination, and the test gas concentration is measured at the exhaust and compared to the average in the room. The CRE index is then calculated by means of Equation 1.

Equation 1

$$\text{CRE index} = \frac{\text{concentration of airborne contaminants in exhaust}}{\text{average airborne concentration of contaminants in room}}$$

Equation 1 can be used in situations where no test contaminants enter the room in the air supply and is directly applicable to rooms that do not recirculate air but use fresh outside air. Where the air is recirculated, the concentration of contamination added to the room is measured and deducted. In cleanrooms, recirculation of air is normal and will add large quantities of test gases to the cleanroom and reduce the accuracy of the measurements. Particles are the best test contaminant to use in cleanrooms as high-efficient filters will ensure that the air supply is particle-free and, additionally, airborne particle counters and particle generators are widely available in cleanrooms.

In a cleanroom, the CRE index can be measured by constantly releasing small test particles (usually ≥0.3 μm or ≥0.5 μm) at the source of contamination. Alternatively, particles that are normally emitted during manufacture can be used. The particle concentration should be allowed to build up to the steady-state condition, where the rate of generation of test contaminants in the room is balanced by their removal through the exhausts, and the particle concentration is reasonably constant. The particle concentration is then measured. Further information about the 'steady state' condition is given elsewhere[7].

Obtaining the concentration of airborne contaminants in a cleanroom's exhaust is a relatively simple task but obtaining the overall average in the room is more difficult, as the concentration is likely to vary round the room. Therefore, the concentration should be obtained by either, (a) stopping both the air supply and release of test contaminants, and measuring the concentration of test contaminants after they have been thoroughly mixed by a room fan; or (b) measuring the concentration at multiple locations round the cleanroom, and calculating an average. Other approaches can be used, such as measuring the airborne particle concentration at each of the exhausts, and obtaining an average by weighting these concentrations by each exhaust's air volume rate, but these alternative methods are likely to require more effort.

The CRE index is suggested for use in situations where contamination comes from a fixed source of contaminants, as the index will vary according to the position of the source, and will be high when sources such as personnel and machinery are close to the exhaust, and reduced when they are further away.

The CRE index gives information about the ventilation system's ability to control contaminants being emitted from a source but not how effective the ventilation is in providing a low level of airborne contamination. This can be illustrated by considering a critical location that is between the source of contaminants and the air exhaust or exhaust hood. In that situation, the source's airborne contaminants will be drawn to the exhaust and in doing so could contaminate the product as they pass by. Therefore, the CRE index can indicate that the ventilation of the cleanroom is working well with respect to removing contaminants, but fail to show that the risk to product from airborne contamination is increased.

If airborne contaminants are perfectly mixed with room air, the concentration of airborne contaminants at the exhaust will be the same as any location in the cleanroom, and the CRE index will be 1. If airborne contaminants from a source are efficiently removed from a cleanroom, the CRE index will be greater than 1, and if the airborne contaminants are inefficiently removed it will be less than 1. The CRE index can have values close to 1 but it is not unusual to have very large or very small indexes.

Air Change Effectiveness (ACE) index

A standard method for measuring the ACE index in ventilated rooms is described in ANSI/ASHRAE (American National Standards Institute/American Society of Heating and Refrigeration and Air-Conditioning Engineers) 129-1997 (RA 2002)[8]. An ACE index is also described in the REHVA Guidelines[1] that is very similar to the ASHRAE standard, but its method of calculation gives it a value that is half the ASHRAE index. The ACE index, as calculated by the ASHRAE standard, is described and discussed in this article.

The ASHRAE standard method requires the ACE index to be measured at an important location, or locations, in a mechanically ventilated room. The main location suggested in the ASHRAE standard is where a person breathes. In cleanrooms, the amount of fresh air is also important but is unlikely to be a problem because of the large air supply rate that is likely to contain more than sufficient amounts of fresh air. The main problem in cleanrooms is at critical locations where products or processes are exposed to airborne contamination.

The equation given in the ASHRAE standard to

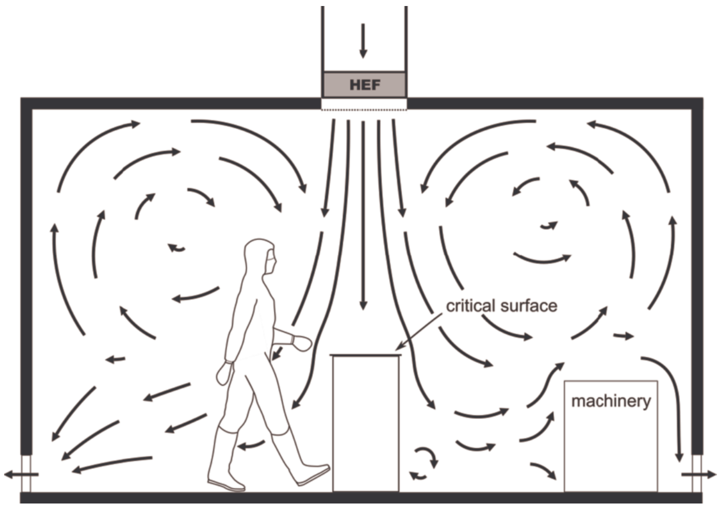

Figure 3. Major airflows in a non-UDAF cleanroom without an air diffuser at the air inlet.

calculate the ACE index (called 'ACE' in the ASHRAE standard) is as follows.

Equation 2

$$\text{ACE} = \frac{\tau_n}{A_i}$$

Where,
τ_n = nominal time constant, and
A_i = age of air at location, i.

Both the 'nominal time constant' and 'age of air' are terms unfamiliar to most cleanroom designers and users. However, it has been shown[4] that the ACE index can also be obtained by the following alternative equation that compares the local air change rate at the measuring location, which is normally a critical location, with the overall average in the cleanroom.

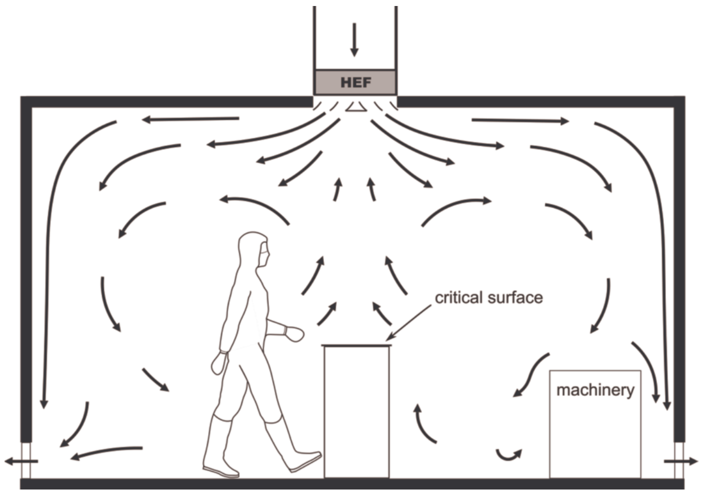

Figure 4. Major airflows in a non-UDAF cleanroom with a four-way diffuser at air inlet.

Equation 3

$$\text{ACE index} = \frac{\text{air change rate at measuring location}}{\text{overall average air change of cleanroom}}$$

As will be demonstrated later in this article, the air change rate at a location is the same as the recovery rate measured by the method described in ISO 14644-3: 2005 Test Methods[2]. Therefore, a further equation can be used to calculate the ACE index in cleanrooms that is as follows.

Equation 4

$$\text{ACE index} = \frac{\text{recovery rate at measuring location}}{\text{overall average air change rate of cleanroom}}$$

As can be understood from consideration of Equation 3, if supply and room air are perfectly mixed, the ACE index will have a value of 1 at all locations in the cleanroom. If less clean air reaches the measuring location than the room's average, the ACE index will be below 1. If more clean air reaches the location, the ACE index will be above 1. Therefore, when designing the airflow within a cleanroom the object is to ensure the ACE index will not be below 1 at a critical location. The method of measuring the ACE index will be discussed later in this article. Some typical values of ACE indexes in non-UDAF cleanrooms have been published[4,9].

Shown in **Figure 3** are major airflows that are typically found in a non-UDAF cleanroom where the air inlet is without a diffuser and the cleanroom air is exhausted at low-level. The airflow patterns in **Figure 3** were obtained from experimental measurements and CFD analysis[5]. The ACE indexes were also measured using the experimental method described in the section in this article that is entitled 'Calculation of the ACE index in cleanrooms'. It can be seen that the major air flow from the air inlet is downwards and this results in the area below the diffuser having better than average cleanliness conditions, and an ACE index greater than 1. However, other areas of the cleanroom have poorer airborne conditions and ACE indexes of less than 1, and if the same cleanliness conditions are required in all areas of the cleanroom, this design approach is unsuitable. Also, if the critical location could change during the planning stage, or during the years of manufacturing, this ventilation design is not a good choice.

An alternative design that can be used in non-UDAF cleanrooms to overcome problems associated with air inlets without diffusers is to use air diffusers that efficiently mix supply and room air. Shown in **Figure 4** are typical airflows from this type of ventilation that are obtained from an experimental and CFD study[5]. This design ensures a similar quality of airborne cleanliness and reasonably constant ACE indexes of 1 throughout the room, and this will be maintained if changes are made to the position of the critical location. This is often the best approach for general ventilation design of a non-UDAF cleanroom, and if better than average quality of air must be provided at a critical location, a clean air device should be used.

Performance Index (PI)

Another VE index that can be successfully used in a cleanroom is the PI, which was one of the earliest indexes used to demonstrate the effectiveness of different types of ventilation systems in clean areas, namely in operating theatres[10]. The PI compares the concentration of airborne contaminants at a critical location to the average concentration in room air, and is calculated by Equation 5.

Equation 5

$$PI = \frac{\text{average concentration of airborne contaminants in whole room}}{\text{concentration of airborne contaminants at critical location}}$$

The measurement of the PI must be carried out in the steady-state condition, where the rate of dispersion of contaminants into a cleanroom equals that removed through the exhausts, and the airborne particle concentration remains relatively steady. This condition is different from that used to measure the ACE index, where the decay of airborne contaminants is measured. The PI can be obtained by introducing a steady stream of test particles into a cleanroom, and allowing the concentration to build up to the steady-state concentration. When the steady-state condition has been reached, the airborne contaminants at the critical location and the average concentration in the whole room are determined. The average concentration can be obtained from measurements at several locations in the room, or by measuring the particle concentration and air volume flow at each exhaust, and obtaining an average concentration by weighting the concentrations with the airflow volumes. The PI is then calculated using Equation 5.

An alternative method of measuring the PI is to use the particles dispersed from normal sources of contaminants, such as personnel and machines, in an operational cleanroom. This is a useful approach, as it overcomes any objections to additional contamination from test particles. It also overcomes the problem of where test particles should be released, as the PI is strongly influenced by the flow of air taking particles towards, or away from, the critical location. In addition, contaminants are normally released from several sources, including personnel who are not usually static. It is therefore difficult to know the best place to release test contaminants, and this problem is overcome by using naturally occurring particles found during normal operational conditions.

If the air in a cleanroom is well mixed, the PI at all locations will be 1. If more clean air than average reaches the critical location, or contaminants are less likely to be transferred from sources, the PI will be greater than 1. If more contaminants, or less clean air, than average reaches the critical location, the PI will be less than 1. Thus, the PI shows how the airborne cleanliness at a critical location compares to the cleanroom's average. Values of the PI have been measured in cleanrooms[5].

The measurement of the PI in a non-UDAF cleanroom can be obtained by measuring naturally occurring airborne particles of a size of either ≥0.5 μm or ≥0.3 μm. If, for example, the average concentration in the cleanroom in the steady-state condition during manufacturing was 26,000/m^3 and the concentration at the critical location was 20,000/m^3, the PI as calculated by Equation 5 would be 1.3. This result shows that the critical location has a lower airborne concentration than average, and the ventilation is satisfactory.

Decay of airborne contamination in non-UDAF cleanrooms

General expression of exponential decay

The decay of the property of some substances, such as radioactive material or the temperature of an object in a stream of cooling air, occurs in an exponential manner. A general equation can be applied to the exponential decay that allows the concentration of the property to be calculated over time.

Equation 6

$$C = C_0.e^{-\lambda t}$$

Where,
C = concentration after time t,
C_0 = initial concentration,
e = Euler's constant = 2.72,
λ = decay constant, and
t = elapsed time.

The rate of exponential decay will vary from situation to situation and is determined by λ, which is known as the 'decay constant', although it is the rate that the property decays. Exponential decay occurs in non-UDAF cleanrooms when airborne contaminants are diluted with supply air and, in that situation, λ is equal to the air change rate.

Decay rate calculations in non-UDAF cleanrooms

During cleanroom manufacturing, particles are dispersed into the air by sources of contaminants such as personnel and machinery. However, when dispersion stops, or reduces, the particle concentration will decay. This occurs in situations where personnel leave a clean zone, and machinery and process equipment are switched off, or at the termination of the introduction of test particles used to measure the recovery rate according to ISO 14644-3: 2005. The decay rate is normally measured using small particles (either ≥0.3 μm or ≥0.5 μm) to avoid an additional reduction by gravitational deposition on surfaces that occurs with larger particles. The airborne particle concentration decays in an exponential manner, and can be calculated by Equation 7, where the decay constant (λ) is the air change rate. It should be noted that the equation only applies to non-UDAF cleanrooms where supply and room air is well mixed with airborne contamination, and not to UDAF cleanrooms where the air flows in a unidirectional manner and minimal mixing of air occurs, and particle concentration decay cannot be expressed in an exponential manner.

Equation 7

$$C = C_0 . e^{-Nt}$$

Where, N is the air change rate

The decay of the concentration per m^3 of airborne particles (≥0.5 μm) in a non-UDAF cleanroom, when the dispersion of test particles stops, is shown in **Figure 5**. The decays are shown for 20, 40 and 80 air changes per hour, and the particle concentrations calculated by Equation 7 as a percentage of the initial concentration. The plots show the typical characteristics of exponential decay, where the decay becomes less as time progresses and the concentration never touches the x-axis, i.e. it is asymptotic to the axis. If the y-axis had used a logarithmic scale, the plots would have been straight lines.

It should be noted that the same decay rate applies to all non-UDAF cleanrooms with the same air change rate, irrespective of the size of the cleanroom. This information also demonstrates the fact that one air change per unit of time does not mean that all the air in the non-UDAF cleanroom is removed in the one unit of time and, for example, 20 air changes per hour does not mean the cleanroom is free of particles in 3 minutes.

The time for airborne contaminants to decay from an unacceptably high concentration to a suitable lower concentration can be obtained from **Figure 5**. This time can be used for (a) designing airlocks to ensure airborne contaminants are reduced to an acceptable concentration before a door into a clean area is opened[3]; (b) calculating the time needed to lower the concentration of airborne particles when the normal air supply is reinstated after a 'set back' during a period of inactivity; and (c) calculating the time it takes for a non-UDAF cleanroom with a known air change rate and particle concentration to conform to the 'clean up' requirements set by the EU Guidelines to Good Manufacturing Practice[11,12]. These times can be calculated by Equation 8 that has been obtained from a rearrangement of Equation 7.

Equation 8

$$t = -\frac{1}{N} \ln \frac{C}{C_0}$$

If an example is taken of a non-UDAF cleanroom with 20, 40 and 80 air changes per hour, it can be calculated that it will take approximately 14, 7 and 3 minutes to remove 99% of the airborne particles. A reduction of 95% will take 9, 4.5 and 2.3 minutes, respectively. Other reductions can be calculated by use of Equation 8.

Equation 8 assumes perfect air mixing in the cleanroom. However, where ventilation effectiveness is poor, the ACE index can be used to correct the equation.

Equation 9

$$t = -\frac{1}{N.\text{ACE}} \ln \frac{C}{C_0}$$

If, for example, the ACE index is 0.7, the decay time will have to be increased by a factor of 1/ACE, i.e. 1.43.

Equation 7 can also be rearranged to calculate the air change rate (N) from knowledge of the particle decay.

Equation 10

$$N = -\frac{1}{t} \ln \frac{C}{C_0}$$

When logarithms to the base 10 are used, the following Equation 11 is used to determine the air change rate.

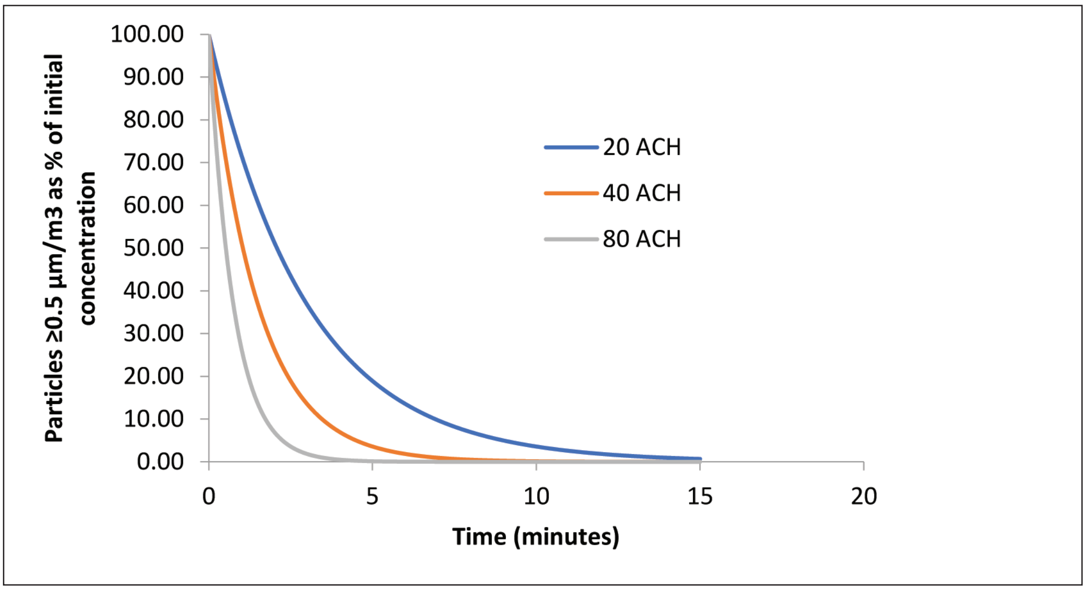

Figure 5. Decay of airborne particles; ACH: air changes per hour.

Equation 11

$$N = -2.3 \times \frac{1}{t} \log_{10} \frac{C}{C_0}$$

Recovery rate measurements according to ISO 14644-3: 2005

The ability of a cleanroom's ventilation system to rapidly reduce airborne contaminants after a temporary emission of contaminants can be determined in a non-UDAF cleanroom by measuring the decay rate of test contaminants introduced into the cleanroom. Two methods are given in ISO 14644-3: 2005 Test Methods, and known as 'recovery time' and 'recovery rate'. Both methods are closely related. The first method measures the time for test particles to decay to either 1/100th or 1/10th of their initial particle concentration and the second method obtains the recovery rate from the decay rate of the test particles that have been introduced into the room. The decay rate is equal to the recovery rate, and the following Equation B12 is given in ISO 14644-3: 2005 to calculate the recovery rate.

$$n = -2.3 \times \frac{1}{t} \log_{10} \frac{C}{C_0}$$

Where n is the decay or recovery rate.

The recovery rate method of ISO 14644-3 has been shown to be the potentially more accurate of the two tests and has the additional advantage that it can be used to obtain the ACE index. The fact that the recovery rate is the same as the decay rate is confirmed by comparing Equation 11 with Equation B12 of ISO 14644-3: 2005. It can be seen that the right-hand side of both equations are identical and therefore the left hand side of the equations must also be identical and N, the air change rate, must equal n, the recovery rate.

Measurement of air change rate by decay rate

The usual method of calculating the overall air change rate in a non-UDAF cleanroom is to measure the room's air supply rate and, knowing the room's volume, use the following equation.

Equation 12

$$\text{Air change rate/hour} = \frac{\text{air supply rate (m}^3\text{/hour)}}{\text{volume of room (m}^3\text{)}}$$

However, this calculation can only be used when the air volume supply rate to a room is known. If the air supply rate is unknown, such as occurs in rooms in naturally ventilated homes where there is no mechanical ventilation, an alternative method must be used, such as described in American Standard for Testing and Materials (ASTM) Standard E741: Standard Test Methods for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution[13]. However, it should be noted that when the air change rate is obtained by this method, the result does not apply to the whole room but only to the location where the air is drawn into the sampler.

The ASTM standard gives alternative methods for measuring air change rate, and the most commonly used is the decay method. A test gas is introduced into the room and, after its introduction, the air supply is stopped and the test gas is then well mixed with room air. The air supply is then switched on, and the test gas concentration measured as it decays. As previously discussed, Equations 10 or 11 can then be used to calculate the air change rate.

$$N = -\frac{1}{t} \ln \frac{C}{C_0} = -2.3 \times \frac{1}{t} \log_{10} \frac{C}{C_0}$$

A further equation that is given in ASTM E741 can be used and is as follows.

Equation 13

$$N = (\ln C - \ln C_0)/t$$

Using one of these three equations, the air change rate at a measuring location is obtained from the decay of test contaminants introduced into the room. A test gas, such as SH_6 or N_2O, is used in ordinary mechanically ventilated rooms such as offices, but in cleanrooms where room air is recirculated, particles can be used, as high-efficient filters will ensure that the air supply is free of particles and more accurate measurements are obtained.

When the above information in this section and previous sections is considered, it can be understood that, at the same measuring location,

Decay rate = Recovery rate = Air change rate

Practical example of calculating the decay/recovery/air change rate

To demonstrate how the recovery rate or air change rate may be obtained at a location in a non-UDAF cleanroom, a worked example is now considered. A method is given in ISO 14644-3: 2005 to calculate the recovery rate, and in ASTM E741 to obtain the air change rate. Both methods are almost identical and measure the decay rate of airborne contaminants introduced into a room. In the ISO 14644-3 recovery rate method, the air conditioning system is usually kept running in order not to compromise cleanliness, and mixing of room air and test particles is obtained by the normal airflow in the room. In the ASTM method, the mechanical ventilation is switched off, the test particles mixed with a room or desk fan, and the ventilation switched back on. In this example, the method suggested in ISO 14644-3: 2005 is used.

To carry out the test, a burst of an aerosol of particles should be introduced into the cleanroom. This would normally be obtained from either an aerosol generator of the type used for testing leaks in air filters, or a generator used for the visualisation of airflow patterns. The introduction of the particles should be stopped after several seconds, to ensure that the particle concentration is

Table 1. Decay of test particles over time.

Elapsed time (minutes)	1	2	3	4	5	6
Concentration/m³	7,484	45,437,172	70,000,000	60,221,165	32,618,647	14,530,327
Elapsed time (minutes)	7	8	9	10	11	12
Concentration/m³	6,021,721	2,336,013	945,793	380,781	182,219	94,357

no higher than that recommended to avoid coincidence measurement of particles in the airborne particle counter. However, if the concentration is above that figure, it can be allowed to decay to a suitable concentration before readings are registered. Actual results of a decay of the concentration of test particles ≥0.5 μm in a non-UDAF cleanroom are given in **Table 1**.

The results in **Table 1** are shown graphically in **Figure 6**. The calculation of the decay rate must be carried out over the period of exponential decay, and this period can be ascertained by plotting particle concentrations over time. It is shown in **Figure 6** that there are areas where (a) mixing occurs; (b) exponential decay occurs; and (c) background concentration affects the decay. It can also be seen that it took several minutes of mixing before the exponential decay was established, and after 10 minutes the background count of particles in the cleanroom reduced the rate of exponential decay. It should be noted that the air change rate in this example was about 67 air changes per hour. If the air change rate is lower or higher, the mixing time will increase or decrease, respectively, and it is best that the results are plotted to identify the period of exponential decay.

The y-axis scale of **Figure 6** is logarithmic and, therefore, the exponential decay is identified by a straight line. This occurs between an elapsed time of about 6 and 10 minutes. The decay and, therefore, the recovery rate over this period can now be calculated as follows.

$$\text{Recovery rate} = n = -2.3.\frac{1}{4}.\log\frac{C}{C_0} =$$

$$= -2.3.\frac{1}{4}.\log\frac{380781}{32618647} = 1.1/\text{min} = 67/\text{hour}$$

As the air change rate is identical to the recovery rate, both the air change rate and recovery rate at the measuring location are 67/hour. This information can now be used to obtain the ACE index at the measuring location.

Calculation of the ACE index in cleanrooms

The ACE index can be calculated by the previously discussed Equations 3 and 4.

$$\text{ACE index} = \frac{\text{air change rate at measuring location}}{\text{overall average air change of cleanroom}}$$

$$= \frac{\text{recovery rate at measuring location}}{\text{overall average air change rate of cleanroom}}$$

To solve these equations, it is necessary to obtain the recovery or air change rate at a critical location and compare it with the air change rate of the whole room. To demonstrate the calculation, the worked example discussed in the previous section is again used.

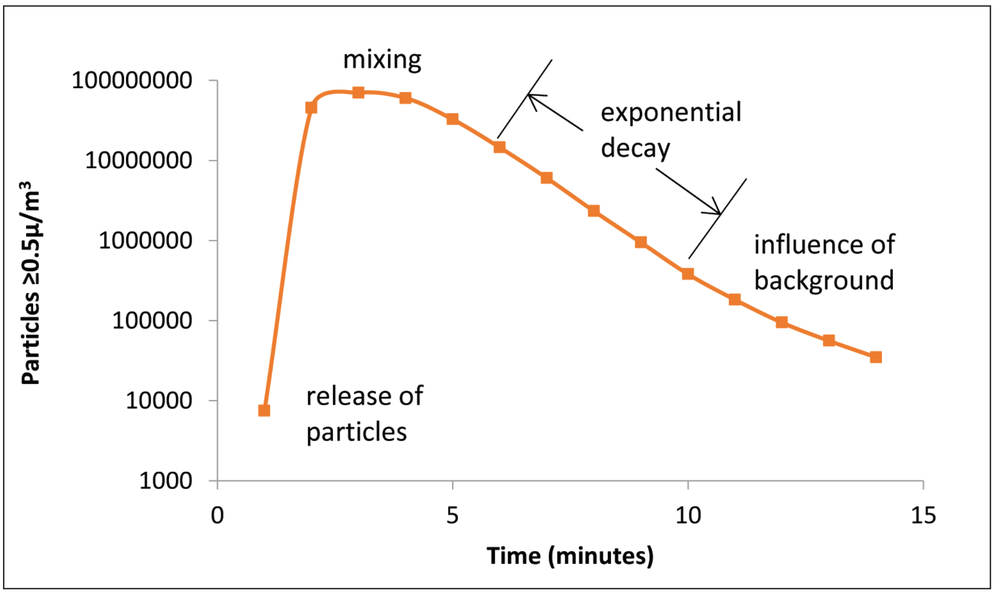

Figure 6. Airborne particles concentration during the recovery rate test.

The cleanroom used in the worked example is a non-UDAF cleanroom with a floor area of 6 m x 5 m and a height of 3 m, i.e. a volume of 90 m^3. The air supply rate to the cleanroom was accurately measured and found to be 0.58 m^3/s, and using Equation 3 the air change rate of the whole cleanroom was calculated to be 50 air changes per hour. Alternatively, the decay of test particles can be measured at each exhaust and the air change rate determined. The air volume rate passing through each extract should also be measured and used to obtain a weighted average of the overall air change rate of the cleanroom. Using this method, it was confirmed that the average overall air change rate was 50/hour.

Knowing the recovery and air change rate per hour at the critical location was 67, the ACE index at the location can be calculated to be 67/50 = 1.3. This result shows that the supply of clean air to the critical location is greater than average and, therefore, the ventilation of the cleanroom is satisfactory.

Discussion and conclusions

Cleanrooms are supplied with large quantities of filtered air to dilute airborne contaminants dispersed from sources in the cleanroom. However, owing to the placement of air inlets and exhausts, use of air diffusers, obstructions to airflows, and thermal effects, the airflow within the cleanroom may not be as effective as it should be, and critical locations may not receive sufficient filtered air to minimise airborne contamination. To ensure that effective airflow is obtained, VE indexes can be used during the design and commissioning of new or upgraded cleanrooms, or during manufacturing operations.

Types of VE indexes are considered in this article, namely, the CRE and ACE indexes and the PI. The ACE index and PI are considered to be the most suitable for cleanrooms. The ACE index compares the air change or recovery rate measured at a critical location with the overall air change rate of the cleanroom, and the PI is obtained by comparing the concentration of contaminants at a critical location with the overall average concentration.

ACE indexes are measured in ordinary ventilated rooms such as offices, but a method that is more suitable for cleanrooms is described in this article. The method is based on the calculation of the recovery rate that is described in ISO 14644-3: 2005. The recovery rate is shown to be the same as the air change rate when measured at the same location, and if the recovery or air change rate at a critical location is compared with the overall air change rate of the room, the ACE index is obtained.

Another VE index that is useful in cleanrooms is the PI, which compares the airborne concentration of contaminants at a critical location with the average concentration in a cleanroom, and demonstrates whether a critical location is receiving an adequate supply of filtered air and that the dispersion of contamination from sources is controlled. The PI can be measured by releasing an aerosol of test particles at the source of contaminants, but it is more useful and more easily measured, if naturally occurring particles dispersed in an operational cleanroom are used. This has the advantage of avoiding the problem associated with the selection of the position to release test contaminants, and also allow the ventilation effectiveness to be obtained during actual working conditions.

The measurement of VE indexes is a useful test that shows that the air supply in a non-UDAF cleanroom is being effectively used to dilute and remove airborne contaminants. If the recovery rate is routinely measured according to ISO 14644-3, then a little extra work is required to compare the recovery and air change rate at a location with the overall air change rate, and obtain the ACE index. The PI index can be obtained by measuring the airborne particle concentration at a critical location during operational conditions and compared with the overall average concentration in the cleanroom. Use of VE indexes will give an additional contribution to methods of controlling contamination in cleanrooms.

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