Isokinetic sampling of airborne particles in cleanrooms

W Whyte

Abstract

The concentration of airborne particles in cleanrooms and clean zones is normally measured by a light scattering airborne particle counter (LSAPC) and, to obtain accurate measurements, losses of particles should be avoided. In this article, the loss of larger particles at the inlet of a sampling probe in unidirectional airflow is investigated. The reasons for the losses of larger particles are described, and the magnitude of the losses is calculated. It is shown that in a typical cleanroom, where the air velocity in the sampling probe is likely to be greater than the air approaching the probe, particles below 1µm will have insignificant losses, particles between 1µm and 5µm will have a small loss, and particles above 5µm will have substantial losses.

Introduction

When particles are measured in the air of cleanrooms, there are several mechanisms that can cause losses of particles, and inaccurate measurements. The various mechanisms are described in detail in textbooks on particle aerodynamics.[1, 2, 3] Information on how these mechanisms apply to cleanrooms has been supplied in ISO/TR 14644-21: 2023,[4] and described in the article written by Olivier Brouste that is published in the same edition of this journal as this paper.[5]

In unidirectional airflow cleanrooms and clean zones, it is necessary to minimise the losses of particles at the entrance of a sampling probe, and this is achieved when the velocity of the unidirectional airflow approaching the entrance to the probe is the same as the velocity of the air in the probe i.e. the airflow is isokinetic. To ensure this occurs when an LSAPC is used to directly sample airborne particles in unidirectional airflow cleanrooms and clean zones, a correctly designed isokinetic sampling probe of the type shown in Figure 1, should be used. In a similar way, when a sampling tube is used to connect from a remote sampling location to an LSAPC, an isokinetic probe of the type shown in Figure 2 should be used at the entrance to the tube.

Isokinetic sampling

The intake of an isokinetic probe should be designed to ensure that the velocity of the unidirectional airflow approaching the probe is the same as the airflow velocity entering the probe. This will ensure that both small and large particles will smoothly enter the intake, with no change in their direction, and result in a near perfect sample of particles. This is shown in Figure 1.

The concentration of particles in unidirectional airflow will be inaccurately measured if the airflow velocity at the entrance to the probe is different from the air velocity approaching the probe i.e. it is an-isokinetic. The reason for this is explained by consideration of Figures 4 and Figure 5.

In Figure 4, the velocity of the unidirectional airflow approaching the probe is lower than the airflow velocity in the entrance to the probe. This sampling condition is known as super-isokinetic. It is caused by the air sampling rate of the LSAPC producing a higher airflow velocity into the probe than that of the unidirectional air approaching the probe. This causes air outside the inlet to be drawn into the probe in the manner shown in Figure 4. At the probe edge, larger particles with

Figure 1: LSAPC with isokinetic sampling probe

Figure 2: Isokinetic probes for sampling 2.8, 28, and 100 L/min of air (normally turned to face unidirectional airflow)

sufficient mass are not able to follow the turn of the air stream into the probe, and are thrown outside the probe, and the air sample measured by the LSAPC will have a lower concentration of larger particles than the actual concentration in the cleanroom.

Figure 5 shows sub-isokinetic sampling of air, where the velocity of the unidirectional airflow approaching the probe is higher than the airflow velocity at the entrance to the probe. This condition is unlikely to occur in a cleanroom, as the air sampling rate of the LSAPC will normally cause the air velocity in the probe to be higher than the unidirectional airflow approaching the probe. Because of the lower airflow in the probe, the air will turn away from the entrance of the probe in the manner shown in Figure 5. At the probe edge, larger particles with sufficient mass are not able to follow the turn of the air stream around the probe and are thrown into the inlet of the probe. Therefore, the air sample measured by the LSAPC will have a greater concentration of larger particles than the actual concentration in the cleanroom air.

If we consider the previous paragraphs, it can be understood how super- and sub-isokinetic sampling change the measurement of the airborne concentration of larger particles when sampling in unidirectional airflow. However, smaller particles that are around 0.3µm and 0.5µm in diameter will react in a different way. Because of their low mass, these small particles will not leave the air stream and are not thrown into, or away from, the probe entrance in the manner of larger particles. As the LSAPC samples a constant volume of air, and no smaller particles are lost or gained, it follows that there will be no change to their concentration in either the super-isokinetic or sub-isokinetic condition.

It should be noted that the air streams in Figure 3 could give the false impression that more air, and therefore, more smaller particles are drawn into the probe. Similarly, Figure 4 could give the false impression that less air, and fewer smaller particles are drawn into the probe. Neither of these interpretations are correct, as the drawings show the direction of the airflow, and not the quantity of air flowing into the probe.

In summary, larger particles tend to maintain the direction of their original pathway when the airflow changes direction. Because of this, super-isokinetic sampling will sample a smaller proportion of larger particles, and sub-isokinetic sampling will sample a greater proportion. However, smaller particles will move with the path of the airflow, and no additional particles are thrown into or away from the probe entrance, and the concentration of smaller particles will be correct.

Calculation of the diameter of the intake of an isokinetic probe

To obtain isokinetic sampling, and avoid losses or gains of larger particles, the air velocity entering the probe should be the same as the unidirectional airflow velocity of the airflow approaching the probe (as shown in Figure 3). This is achieved by sizing the probe entrance to obtain an airflow velocity into the probe that is the same as the airflow velocity of the air approaching the probe.

How the required diameter of a probe needed for isokinetic conditions can be determined is demonstrated by an example of an LSAPC with a sampling rate of 28.3L/min (0.000472m^3/s). Its sampling probe is set up to face oncoming unidirectional airflow with an airflow velocity of 0.45m/s. To obtain the correct size of probe, the required surface area of the intake of the probe is calculated as follows:

Equation 1

$$\text{Surface area of probe intake } (\text{m}^2) = \frac{\text{sampling rate of LSAPC } (\text{m}^3/\text{s})}{\text{approaching UDAF velocity } (\text{m/s})}$$

After determining the surface area of the intake, the diameter of the probe intake is calculated, and for a LSAPC with a sampling rate of 28.3L/min the probe's intake diameter is 3.65cm. If the sampling rate of the LSAPC is 50L/min or 100L/min, the diameter of the isokinetic intake should be 4.86cm and 6.87cm, respectively.

Information given in ISO/TR 14644-21 about isokinetic sampling

The information discussed in the previous paragraphs is the accepted explanation of the mechanism of isokinetic and an-isokinetic sampling.[1, 2, 3] However, the following information is given on page 11 of ISO/TR 14644-21: 2023.

'Super isokinetic sampling will typically yield an increase of smaller particles in relation to large particles, as the smaller particles are more likely to be redirected through the airstream, and the smaller available opening restricts the sampling of large particles, that retain more momentum within the airstream and remain unsampled. Sub isokinetic sampling offers a larger opening for oversampling large particles, but the airstream lines are now deflected due to a positive pressure at the inlet to the Isokinetic sampling probe, that causes the smaller particles to be under sampled.'

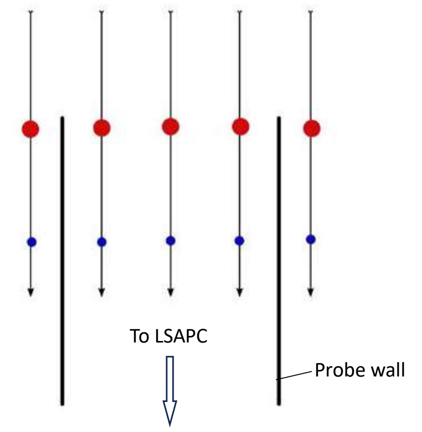

Figure 3: Isokinetic sampling (not to scale)
● = larger particles, ● = smaller particles

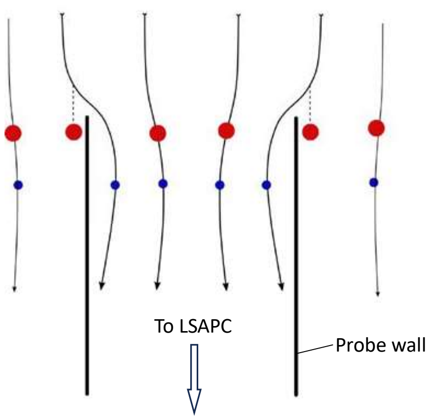

Figure 4: Super-isokinetic sampling
● = larger particles, ● = smaller particles

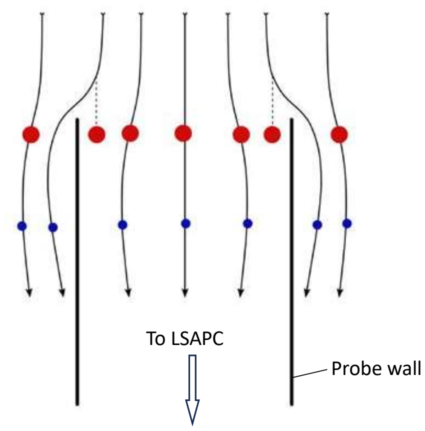

Figure 5: Sub-isokinetic sampling (not to scale)
● = larger particles, ● = smaller particles

The explanation in ISO/TR 14644-21:2023 of losses or gains of airborne particles during sampling is not clear, but it can be interpretated to mean that during super-isokinetic sampling (Figure 4) the concentration of smaller particles will increase, and the larger particles will decrease, or it can be interpretated to mean that there is an increase of the ratio of small particles compared to larger particles. During sub-isokinetic sampling, ISO/TR 14644-21: 2023 appears to say that there will be an increase in the concentration of larger particles but a decrease in the concentration of smaller particles. This information appears to be contrary to the accepted explanation of isokinetic sampling given in this document, and elsewhere.[1, 2, 3] It is hoped that the explanation of isokinetic sampling in this article will clarify the situation.

Calculation of the losses or gains of particles at the intake of an-isokinetic probe during air sampling

The reason for the losses and gains of particles at an intake of a probe when sampling in unidirectional airflow, has been described in the previous part of this article, but the actual losses or gains of particles are now discussed.

Belyaev and Levin (B&L) employed flash photography to investigate the trails of particles as they approached an air intake, and used this information to derive the following Equation 2[6, 7]. This equation is commonly used to calculate the aspiration efficiency (η), which is the measured concentration of particles in the probe compared to the actual concentration in the air being sampled.

Equation 2

$$\eta = 1 + \left(\frac{U_0}{U} - 1\right)\left(1 - \frac{1}{1+k.Stk}\right)$$

Where,

η = aspiration efficiency,

U_0 = air velocity of the air approaching the outside of the probe (m/s),

U = air velocity within the intake of the probe (m/s),

$$k = 2 + 0.62\frac{U}{U_0}$$

Stk = Stokes number.

Stokes number is a dimensionless number that characterises the movement of particles in a fluid such as air, and can be determined by Equation 3. For Stk≥1, particles will follow the fluid streamlines closely.

Equation 3

$$Stk = \frac{\tau\ U_0}{D_s}$$

Where,

Stk =Stokes number,

τ = relaxation time of a particle (s),

U_0 = velocity of the unidirectional air approaching the probe (m/s),

D_s = diameter of sampling probe (m).

The relaxation time (τ) is the time a particle takes to adjust to a change in air velocity, and is determined by Equation 4:

Equation 4

$$\tau = \frac{\rho.d^2}{18\eta}$$

Where,

ρ = particle density = 1000 kg/m^3,

d = equivalent aerodynamic particle diameter (m),

η = viscosity of air, which is 1.81 x 10^{-5} (Pa.s) at standard conditions of temperature and pressure (20°C and 101kPa),

It should be noted that airborne particles found in cleanrooms and other spaces, are irregular in shape, and have various densities. The size of an airborne particle and its movement in air is therefore best investigated by using its equivalent aerodynamic diameter, which is the diameter of a spherical particle with a standard density of 1000kg/m^3 (1g/cm^3) that moves in air at the same velocity and direction as the particle being considered.

B&L used experimental conditions with Stokes numbers (Stk) that ranged from 0.18 to 2.03 to derive their equation. The air velocity ratio (R), which is the ratio of the freestream velocity approaching the probe (U_0) to the velocity within the probe (U) i.e. U_0/U was between 0.17 and 5.6. Investigations have shown that within these ranges, the B&L equation gives accurate results, but outside these ranges, the equation is likely to be less accurate[8, 9, 10, 11].

Should accurate results of the loss of particles at the probe intake be required, or should the design of the intake probe be unusual, computational fluid dynamics (CFD) methods can be used[12]. Commercial CFD software is available that will accurately model the airflow and particle losses. However, the B&L equation offers a simple method of calculating particle losses at an intake probe and should be sufficiently accurate to demonstrate the importance of isokinetic sampling, and to derive the sizes of airborne particles that require isokinetic sampling in cleanrooms.

Example of losses of particles at a probe inlet

To demonstrate the effect of an-isokinetic sampling on the concentration of particles in a typical cleanroom situation, an example is investigated where an isokinetic probe is not used during sampling, but the air is drawn directly into an LSAPC, or via a sampling tube. The LSAPC has a sampling rate of 28.3L/min (0.000472m^3/s), and the inlet of the LSAPC or sampling tube is assumed to have a diameter of 0.8cm (0.008m).

Therefore,

Surface area of inlet = $\pi D^2/4 = \pi.0.008^2/4$ = 0.0000503m^2, and,

Intake velocity of probe (m/s) (U) =

$$\frac{\text{air sampling volume (m}^3\text{/s)}}{\text{area of probe intake (m2)}} = \frac{0.000472}{0.0000503} =$$

= 9.4m/s

The velocity of the unidirectional air approaching the entrance to the tube (U_0) was considered to be equal to the unidirectional airflow in the cleanroom, which was 0.45m/s. Therefore, U_0/U = 0.45/9.4= 0.048.

Table 1: Aspiration coefficient for a range of particle sizes during super-isokinetic sampling

Equivalent particle diameter (μm)	0.1μm	0.2μm	0.3μm	0.5μm	1μm	2μm	5μm	10μm	20μm	50μm	100μm
Aspiration efficiency (η)	1.000	1.000	1.000	0.999	0.998	0.990	0.942	0.805	0.517	0.176	0.084

The loss of particle sizes at the inlet of the probe can now be calculated by means of B&L's equation. The aspiration coefficient (η) is calculated, which is the ratio of the concentration of particles entering the probe to the concentration in the air approaching the probe. In the example being considered, where an isokinetic probe is not used, the sampling will be super-isokinetic, and the aspiration coefficients for the example being considered are given in Table 1.

It should be noted that the aspiration efficiencies given in Table 1 are for discrete sizes of particles. They are not cumulative sizes, which are normally used to classifying cleanrooms by the method given in ISO 14644-1[13]. Because cumulative counts include all particles above a specified size, the results given in Table 1 do not give total particle losses, but only the losses for the particle size being considered.

Discussion and conclusions

This article explains the mechanism of losses or gains of airborne particles at the sampling inlet of an LSAPC with or without a sampling tube, and the need for isokinetic sampling. In a typical cleanroom, the velocity in the inlet to a LSAPC or sampling tube is normally higher than the unidirectional airflow approaching the probe (super-isokinetic sampling). This will cause the air movement at the inlet to throw larger particles outside the inlet, and a lower count to be registered by the LSAPC. However, smaller particles will follow the air stream, and there should be no loss or gain of these smaller particles in an-isokinetic conditions. An explanation of isokinetic sampling that is difficult to follow has recently been given in ISO TR 14644-21: 2023, and it is hoped that this article will clarify the explanation.

In a typical cleanroom situation, where the velocity in the probe is greater than the air approaching the probe (super-isokinetic), the losses of particles at the inlet were calculated by Belyaev and Levin's equation, and reported in this article. These calculations show that the concentration of particles less than about 1µm will not be significantly affected by an-isokinetic sampling. Between 1µm and 5µm there will be a small loss of particles, but above 5µm the reduction can be substantial. Therefore, isokinetic sampling should be used to sample particles greater that 5µm.

It should be noted that this article only considers the possible losses of airborne particles at the intake of a probe, and not the losses caused by (a) misalignment of the inlet probe with the oncoming unidirectional airflow, (b) a blunt-edged intake, and (c) deposition and impaction of particles in the tube that transports air from a sampling location to a LSAPC. These losses should also be considered, and minimised.

References

1. Aerosol Technology - Properties, behaviour and measurement of airborne particles - Second edition, WC Hinds. John Wiley and Sons, 1999. ISBN 0-471-19410-7.
2. Aerosol Measurement- Principles, Techniques and Applications -Third edition. Editors: P Kulkarni, Baron PA and Willeke K. John Wiley and Sons, 2011. ISBN 978-0-470-38741.
3. Aerosol sampling – Science and practice. JH Vincent. John Wiley and Sons, 1989. ISBN 0-471-92175-0.
4. ISO TR 14644-21: 2023. Cleanroom and associated control environments - Airborne particle sampling techniques.
5. Brouste O. An example of theoretical and experimental assessment of performance capability of a sampling configuration for continuous monitoring of a grade A isolator filling line. Clean Air and Containment Review, 2024; Issue 50: page 16
6. Belyaev SP and Levin LM. Investigation of aerosol aspiration by photographing particle tracks under flash illumination. Journal of Aerosol Science, 1972; 3: 127-140. https://doi.org/10.1016/0021-8502(72)90149-8
7. Belyaev SP and Levin LM. Techniques for collection of representative aerosol samples. Journal of Aerosol Science, 1974; 5: 325-338. https://doi.org/10.1016/0021-8502(74)90130-X
8. Liu BYH, Zhang ZQ and Kuehn TH. A numerical study of inertial errors in anisokinetic sampling. Journal of Aerosol Science, 1989; 20(3): 367-380. https://doi.org/10.1016/0021-8502(89)90012-8
9. Daniel J. Rader & Virgil A. Marple. A study of the effects of anisokinetic sampling, Aerosol Science and Technology, 1988; 8(3): 283-299. DOI: https://doi.org/10.1080/02786828808959190
10. Lipatov GN, Grinspun SA, Shingaryov GL and Sutugin AG. Aspiration of coarse aerosol by a thin-walled sampler. Journal of Aerosol Science, 1986; 17(5): 763-769. https://doi.org/10.1016/0021-8502(86)90030-3.
11. Paik S and Vincent JH. Aspiration efficiency for thin-walled nozzles facing the wind and for very high ratios. Journal of Aerosol Science, 2002; 33: 705-720. https://doi.org/10.1016/S0021-8502(01)00208-7
12. Kramer M and Afchine A. Sampling characteristics of inlets operated at low U/U ratios: new insights from computational fluid dynamics (CFX) modelling. Journal of Aerosol Science, 2004; 35: 683-694. https://doi.org/10.1016/j.jaerosci.2003.11.011
13. ISO 14644-1: 2015. Cleanroom and associated control environments – Part 1: Classification of air cleanliness by particle concentration.

Acknowledgement

The photograph of a LSAPC with an isokinetic probe that is shown in Figure 1 is reproduced with the permission of Particle Measuring Systems. The photograph of the three isokinetic sampling probes was supplied by Vadim Kalechits.