Review of Calibration and Improvement Methods of Light-Scattering Airborne Particle Concentration

Z L Gao\textsuperscript{1,2,*}, Q D Cheng\textsuperscript{1,2}, G L Zeng\textsuperscript{1,2}, Y Wen\textsuperscript{2}, G F Li\textsuperscript{1,2}, J Chen\textsuperscript{3}, Y B Dong\textsuperscript{2} and Q Z Ji\textsuperscript{2}

1 First Branch Company of Beijing Hangtianhe Science Technology Development Co., Ltd., Changping District, Beijing, 102205, China.
2 Beijing Orient Institute for Measurement and Test, Haidian District, Beijing, 100094, China.
3 Suzhou Sujing Automation Equipment Corporation, Suzhou, 215000, Jiangsu, China.
Email: gz514cast@126.com

Abstract. Clean environment and its internal airborne particle concentration have been paid more and more attention, the demand for use and measurement of light-scattering airborne particle counter, as the main instrument for measuring airborne particle concentration, has increased synchronously. This paper untangles the worldwide standards and specifications for calibration of light-scattering airborne particle counter, analyses the shortcomings of traditional comparative calibration method, introduces the research progress of non-traditional calibration method based on statistical analysis of membrane and scanning electron microscope, then based on the theory of discrete phase model and gas-solid fluid dynamics, puts forward two improved calibration methods to obtain more reliable "true value" of the number of the standard particles passing through the calibrated OPC, to provide an innovative idea for improving the measurement accuracy of airborne particle concentration worldwide.

Keywords. Airborne particle concentration, comparative calibration, aerodynamics, measurement error.

1. Introduction
Particulate pollution in the air is the main source of pollution in the production and processes of medical, microelectronics, precision machinery, aerospace and other industries, accurate evaluation of air cleanliness has become an urgent requirement for the production and product testing [1-6], such as large-scale integrated circuit manufacturing, spacecraft assembly, pharmaceutical production, precision instrument manufacturing, emission of ultrafine particles from motor vehicles, virus aerosol transmission, negative pressure ward operation, etc. Light-scattering airborne particle counter (also known as Optical Particle Counter, OPC) has been widely used to measure the airborne particle concentration in these clean environment and confined space [7-9].

At present, the comparative test method is widely used to calibrate OPC airborne particle concentration in the world, that is, a "precise particle counter" is used to calibrate the "calibrated particle counter". Generally, the "precise particle counter" is another OPC corrected by capability comparison, or a Condensation Particle Counter (CPC) is directly selected, so that a comparative calibration traceability path of "Optical Particle Counter (OPC) – (Condensation Particle Counter) CPC–Aerosol Electrometer (AE)" is established. However, due to the differences in the particle size range, working flow and measured particles of the instruments at the three levels, the comparative
calibration method needs to and improve the accuracy of calibration result continuously, combined with the theory of measurement error and the characteristics of the calibrated OPC itself.

2. Traditional Comparative Calibration Method for Airborne Particle Concentration

2.1. Standards and Specifications for the Comparative Calibration Worldwide

Airborne particle concentration calibration has been highly concerned by worldwide metrology institutes and standardization organizations, there are many standards of OPC airborne particle concentration calibration method. ASTM International implemented ASTM F328-1998 and ASTM F649-2001, which tried to make the particle counting results could be traceable to the voltage pulse signal generated by the instrument itself, but the counting loss caused by instrument design, parameter setting and laser power attenuation couldn't be determined [10].

At present, the OPC comparative calibration method has been widely used for many years worldwide, the "precise particle counter" comes from two sources: one is another OPC after capacity comparison, relevant standards and specifications such as IEST-RP-CC014.1-2006, JIS B9921-1997/2010, JFF1190-2008, JFF 1562-2016, JFF 1864-2020, GB/T 6167-2007, GB/T 29024.4-2017 (equal utilization of ISO 21504-4:2007) and GJB/J 5416-2005, the other is a CPC, which way has been gradually applied worldwide in recent years, relevant standards and specifications such as ISO 21501-4-2007/2018, ISO 15900-2009/2020 and ISO/DIS 27891-2013, to establish the traceability path of "OPC - CPC - AE" [11-14].

2.2. Shortcomings of the Traditional Comparative Calibration Method

Some Shortcomings are found in the method of step-by-step comparative calibration and traceability path of "OPC - CPC - AE". Firstly, based on the measurement principle, the lower limit of particle size measured by CPC is smaller, and the light-scattering measurement is carried out after particle size amplification through the working solution, so that a CPC is essentially an OPC (the physical object of the light scattering cavity is shown in figure 1, and the working principle of OPC is shown in Figure 2). OPC and CPC slightly overlap in the range of particle size, so their coverage is incomplete, what’s more, the sampling working flow is also inconsistent between them (see table 1).

| Category/Specifications | OPC                  | CPC                  |
|------------------------|----------------------|----------------------|
| Particle size range     | 0.1μm~25μm           | 5nm~3 000nm          |
| Sampling flow           | 2.83L/min or 28.3L/min| 0.30L/min~0.60L/min  |
| Maximum concentration   | 100 000/28.3L(≈3.53/cm³) | 7 000/cm³            |
| Working fluid           | —                    | Butanol, isopropanol, water or other |

Secondly, about the standard particle size for calibration, JFF 1562 gives the average particle size range (80~120) nm for CPC calibration, and the standard requires aerosol generator to produce polystyrene standard particle size range of (50~150) nm [15], but JFF 1190 requires that the size of monodisperse particles for calibration is (0.1~10) μm, 0.4μm and 0.6μm are used in the calibration of particle size distribution error, 0.5μm is used in the calibration of particle concentration indication error.

Thirdly, about the working flow setting during calibration, aerosol dispenser and aerosol diluter need to be used for flow matching in the process of calibrating OPC with CPC. For one channel, it is necessary to increase the clean gas flow through a series of clean air injection, mixing and other steps
But the calibration process does not estimate the particle loss in the pipeline or evaluate the uncertainty of additional air replenishment operation, including the 600mm long aerosol diluter pipe and the adsorbed particles at exhaust port outside the dilutor.

Finally, OPC comparative calibration methods, generally used or recognized worldwide, the calibration process is that the precision particle counter and the calibrated particle counter simultaneously sample and extract gas from a sampling chamber containing stable aerosol composed of standard particles [20-24]. The sampling chamber device is generally a buffer (JJF 1190), a mixing box (GB/T 29024.4, ISO 21501-4), a distributor (GB/T 6167) or a sampler (JIS B 9921), etc. (see figure 1).

**Figure 1.** Sampling chamber for comparative method of airborne particle concentration.
So, the sampling chamber must ensure that the sampling flow of the two particle counters in the comparative test is consistent, also the relevant materials, sizes and positions of the sampling tubes, and the aerosol in the sampling chamber always maintains an ideal uniform distribution state, in order that we can try our best to ensure that the precise particle counter can provide a more accurate "true value" of the number of the standard particles for the calibrated OPC. However, in actual calibration process, the measured standard particles cannot be ensured completely similar as in theory between the precise particle counter and the calibrated OPC.

Therefore, whether the OPC or the CPC is used as the "precise particle counter", there is drawback of "uncertainty" in the "true value" of the number of the passing standard particles.

3. Non-traditional Calibration Method for Airborne Particle Concentration

In terms of the improvement of the calibration methods for airborne particle concentration, worldwide relevant metrology institutes put forward the method of measuring air cleanliness by filter (membrane) collection and electron microscope observation, and this method can still be used to count larger particles (particle size greater than 5μm) nowadays, such as GB 50591-2010, QJ 2214-1991 and IEST-RP-CC003.3-2003, but there is no general method to observe and statistical counting of submicron particles (0.5μm for example) under electron microscope in the world.

The research team of Beijing Orient Institute for Measurement and Test (BOIMT) tried to propose a new OPC calibration method for airborne particle concentration and its traceability scheme based on FESEM (Field Emission Scanning Electron Microscope) and AAO (Anodic Aluminum Oxide) template [25-27], building an inferred statistical calibration system of 0.5μm particle concentration (see figure 2), adding membranes at the rear end of the OPC light-scattering chamber’s air outlet to collect the actual passing standard particles, realizing the same measurement gas path, equal gas flux and the same standard particles with the calibrated OPC, carrying out measurement of the settlement loss of standard particles in the light-scattering chamber, designing the inferred statistical counting method for 0.5μm particles based on the original method of microscopic observation and counting of larger particle size particles. According to the actual test results, the OPC calibration method based on AAO and FESEM makes sense in theory, which deviates from the inherent comparative calibration principle, and it realizes the collection, identification, inference statistical count of low flux and submicron particle (such as 0.5μm), and provides a theoretical and experimental basis for obtaining a more reliable "true value" of the number of the standard particles passing through the calibrated OPC.

![Figure 2. Composition of particle concentration measurement system.](image)

4. Improvement Method for Airborne Particle Concentration Calibration

4.1. More Reliable "True Value" Measurement of the Number of the Passing Standard Particles

According to the theory of measurement error, the improvement of the comparative calibration accuracy of airborne particle concentration, also the further uncertainty reduction of measurement results, depends on the accuracy improvement of the "true value", so it must be ensured that the "precise particle counter” has the same measurement gas path, equal gas flux, the same or covering particle size range, the same measured standard particles with the calibrated OPC (see figure 3).
Figure 3. Framework of improved method for light-scattering particle concentration calibration.

4.2. Inferential Statistics Measurement by the "Post, Collection and Check" Way

On the basis of the previous research on airborne particle concentration calibration scheme based on FESEM and AAO template (see figure 4), we can build a more sophisticated mathematical model of the calibrated OPC’s standard particle flow impacting membrane according to the theory of discrete phase model and gas-solid fluid dynamics [28], obtain the probability distribution of the particles collected by the membrane and the pressure parameters of the membrane by simulation (see figure 5), increase the maximum working flow and other performance parameters of AAO template or other filter membranes, calculate the loss of standard particles in the calibrated OPC scientifically, optimize the calculation theory of the standard particle number based on statistical analysis under the scanning electron microscope (SEM), evaluate the uncertainty of measurement results, carry out iterative test, in order to improve and perfect the calibration theory and method based on inferential statistics for low flux and submicron size airborne particle concentration gradually.

Figure 4. Aerodynamic simulation of light-scattering cavity’s outlet structure.

4.3. Direct Measurement by the "Front, Detect and Count" Way

The "front, detect and count" way is more scientific and convenient than the "post, collection and check" one. The "front, detect and count" method mainly utilizes more suitable and effective particle counter or optical instrument, such as FESEM, laser particle size analyser (LPSA), scanning mobility particle sizer (SMPS) and so on [29]. This counter or instrument shall have an internal cylindrical particle signal detector, which can be installed at the front end of the calibrated OPC’s air inlet, without affecting the normal air inlet operation under the normal working flow (see figure 6). What’s more, the counter or instrument should have more accurate measurement accuracy of the particle size and concentration than the calibrated OPC, higher optical resolution or more accurate AD quantization error control, for example. It should be noted that the airborne particle concentration measurement result of the counter or instrument must be traceable to the SI.

Figure 4. Aerodynamic simulation of light-scattering cavity’s outlet structure.
Figure 5. Scheme of standard particle number measurement by "post, collection and check".

Figure 6. Scheme of standard particle number measurement by "front, detect and count".

5. Conclusion and Prospect
In recent years, more and more attention has been paid to the clean environment and its internal airborne particle quantity concentration in the fields of industrial production manufacturing and life, health and environmental safety, the same is true for the improvement of the measurement accuracy of airborne particle concentration, especially after the 2019-nCov virus outbreak, the demand for air aerosol measurement in confined spaces (such as elevators) and quality monitoring of microbial conditions in medical air environment. The improvement of OPC calibration method is one of the key factors to obtain the higher accuracy in measurement.

Analysing the standards and specifications of airborne particle concentration calibration methods worldwide, this paper points out that the traditional comparative calibration method, widely used at present, has drawback of "uncertainty" in principle, according to the theory of discrete phase model and gas-solid fluid dynamics, proposes two improved OPC calibration methods of "post, collection and check" and "front, detect and count" to obtain a more reliable "true value" of the number of the
standard particles, in order to provide some theoretical and methodological innovation ideas for the research field of airborne particle concentration calibration and its traceability worldwide.

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References
[1] Pillai S G, Haldorai K, Seo W S and Kim W G 2021 COVID-19 and hospitality 5.0: Redefining hospitality operations International Journal of Hospitality Management 94 102869
[2] Somsen G A, Rijn C M, Kooij S, Bem A and Bonn D 2020 Measurement of small droplet aerosol concentrations in public spaces using handheld particle counters Physics of fluids 32 121707
[3] Laurentiu P and Daniel D 2021 Performance Evaluation of Particulate Matter and Indoor Microclimate Monitors in University Classrooms under COVID-19 Restrictions International Journal of Environmental Research and Public Health 18 823-9
[4] Chau J P C, Liu X, Lo S H S, Chien W T and Wan X 2020 Effects of environmental cleaning bundles on reducing healthcare-associated Clostridioides difficile infection: a systematic review and meta-analysis Journal of Hospital Infection 106 734-44
[5] Li Y, Wang B, Zhang P, Zhang Y and Zhu J 2020 A novel cleanliness control method for disk amplifiers High Power Laser Science and Engineering 8 1-5
[6] Nowak N, Scheiber K, Pfeil J, Meyer J, Dittler A, Koch T and Kasper G 2020 Sampling and conditioning of engine blow-by aerosols for representative measurements by optical particle counters Journal of Aerosol Science 148 105612
[7] Müller D, Glöckler F and Kienle A 2019 Application of Mie theory for enhanced size determination of microparticles using optical particle counters Applied optics 58 4575-84
[8] Verdier N, Papy J M, Renard J B, Lefèvre M and Agrapart C 2020 Enhanced detection and sizing algorithm to improve LOAC optical particle counter performances Applied Optics 59 10892-901
[9] Li X H and Zhou Z M 2020 Discussion and application of calibration results of dust particle counter Metrology & Measurement Technique 47 55-7
[10] Gao Z L, Ji Q Z, Yuan Y F and Wang H 2013 Analysis on measurement calibration specifications for light-scattering airborne particle counter Standard Science 42-5
[11] Wlasits P J, Stolzenburg D, Tauber C, Brilke S, Schmitt S H, Winkler P M and Wimmer D 2020 Counting on chemistry: laboratory evaluation of seed-material-dependent detection efficiencies of ultrafine condensation particle counters Atmospheric Measurement Techniques 13 3787-98
[12] Steven T, Kenjiro I, Kumiko Y, Yoshiko M, Hiromu S and Jason S O 2020 Determining the cutoff diameter and counting efficiency of optical particle counters with an aerodynamic aerosol classifier and an inkjet aerosol generator Aerosol Science and Technology 2020 54 1335-44
[13] Wang W, Zhao X, Zhang J S, Yang Y X, Yu T Z, Bian J J, Gui H Q and Liu J G 2020 Design and evaluation of a condensation particle counter with high performance for single-particle counting Instrumentation Science & Technology 48 212-29
[14] Peng J C, Zhou Z M and Li X H 2020 Analysis on the quantity value traceability of dust particle counter Metrology & Measurement Technique 47 5-6, 11
[15] Liu J J, Qi T Y, Wang J W and Liu T 2018 Calibration technology and traceability system of particle counter (PNC) Proceedings of the 22nd Symposium on Air Pollution Prevention and Control Technology p 153-9
[16] Wang W, Zhao X, Zhang J, Yang Y, Yu T, Bian J, Gui H and Liu J 2020 Design and evaluation of a condensation particle counter with high performance for single-particle counting Instrumentation Science & Technology 48 212-29

[17] Horender S, Auderset K, Vasilatou K 2019 Facility for calibration of optical and condensation particle counters based on a turbulent aerosol mixing tube and a reference optical particle counter Review of Scientific Instruments 90 075111

[18] Geisler M and Dirischerl K 2020 Direct approach to determine the size setting error and size resolution of an optical particle counter Review of Scientific Instruments 91 045105

[19] Huang Z H, Li J, Qi T Y and Yang G H 2019 Dilution control system in the traceability process of airborne particle counter Metrology Science and Technology 3-6

[20] Tran S, Iida K, Yashiro K, Murashima Y, Sakurai H and Olfert J S 2020 Determining the cut off diameter and counting efficiency of optical particle counters with an aerodynamic aerosol classifier and an inkjet aerosol generator Aerosol Science and Technology 54 1335-44

[21] Horender S, Auderset K and Vasilatou K 2019 Facility for calibration of optical and condensation particle counters based on a turbulent aerosol mixing tube and a reference optical particle counter The Review of Scientific Instruments 90 075111

[22] Sang-Nourpour N and Olfert J S 2019 Calibration of optical particle counters with an aerodynamic aerosol classifier Journal of Aerosol Science 138 105452

[23] Sundararajan M, Devarajan M and Jaafar M 2020 Investigation of surface and mechanical properties of Anodic Aluminium Oxide (AAO) developed on Al substrate for an electronic package enclosure Surface & Coatings Technology 401 126273

[24] Yatinkumar P, Janusas G, Palevicius A and Vilkauskas A 2020 Development of nanoporous AAO membrane for nano filtration using the acoustophoresis method Sensors 20 3833

[25] Gao Z L, Ji Q Z, Chen J, Li G F, Wang R J, Wu J P, Zeng G L, Cheng Q D, Hu W Z and Tang X 2020 Metrological traceability methods for the light scattering airborne particle concentration The International Society for Optical Engineering: 11th International Symposium on Precision Engineering Measurements and Instrumentation (ISPEMI 2020) 37

[26] Gao Z L, Ji Q Z, Chen J, Zhang X B, Zhang W H, Tan J G and Wang C Y 2018 Statistical measurement method of the standard particles through airborne particle counter based on FESEM Proceedings of SPIE (EI: 2019110668812) - The International Society for Optical Engineering: 10th International Symposium on Precision Engineering Measurements and Instrumentation (ISPEMI 2018) 110530 110530I-1-8

[27] Ji Q Z, Gao Z L, Zhang X B and Chen J 2014 Discuss on traceability method of light-scattering airborne particle counter’s counting performance Proceedings of SPIE (EI: 20151200656569) - The International Society for Optical Engineering: 9th International Symposium on Precision Engineering Measurements and Instrumentation (ISPEMI 2014) 9446 94464C-1-6

[28] Wang L B, Li D H, Chen Z G, Sun M Y and Zhu X S 2017 Numerical simulation of force and separation on particles in pulsing airflow Journal of China University of Mining & Technology 46 162-168, 176

[29] Kong W M 2021 The nano-scanning electrical mobility spectrometer (nSEMS) and its application to size distribution measurements of 1.5-25nm particles Atmospheric Measurement Techniques 14 5429-45