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Design of Wide Particle Size Range Aerodynamic Inlet System with New Pre-focus Structure

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Abstract: A new aerodynamic lens injection system has been designed for wide particle size range, which adds virtual impact and pre-focus structure on the basis of traditional PM2.5 lenses. The system has a small volume and successfully improves the focusing ability of traditional PM2.5 lens systems to 100 nm-10 μm. The structure of the new pre-focus hole solves the problem of affecting the transmission and focusing of large particles, effectively reducing the beam width and dispersion angle of particles entering the virtual impactor, significantly improving the focusing effect of large particles, and enhancing the transmission efficiency of large particles. It can also effectively focus particles without significantly accelerating particles, avoiding the structural size of the buffer chamber being too large. Numerical simulation shows that the new injection system can transmit particles with 100% efficiency in the range of 0.2-4 μm particles, and can achieve the transmission of 1-9 μm particles with an efficiency higher than 90%. The standard microsphere experiment verified the good consistency between the performance of the injection system and the simulation results. In the testing of standard Arizona dust, the wide-range particle size distribution obtained by the new injection system is highly consistent with APS 3321. The new injection system combines a new pre-focus structure, a smaller buffer chamber, a five-stage lens, and the whole injection system volume that is up to 90% smaller than previous self-made wide-range lens designs. At the same time, it has ultra-high transmission efficiency, demonstrating the potential for miniaturization of single particle aerosol mass spectrometer in detecting particles with a wide particle size range.

Keywords: Aerosol particles; Aerodynamic lens; Beam width; Transmission efficiency; Numerical simulation

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1 Introduction

As a key component of aerosol mass spectrometry, the particle beam generator is used to focus the injected particles, and the focusing ability of the particle beam determines the detection sensitivity of the aerosol mass spectrometer. As a common particle beam focusing device, aerodynamic lenses (Liu et al., 1995; Murphy et al., 2006; Zelenyuk et al., 2015; Clemen et al., 2020) utilize the inertia difference between particles and fluids to focus particles and are widely used in different aerosol mass spectrometry (Peck et al., 2016). In addition to its application in aerosol mass spectrometry, aerodynamic lens systems have also been applied in many analytical equipment. Researchers use aerodynamic lenses to introduce aerosol particles into pulsed X-ray beams and determine the particle composition using diffraction patterns and ion fragments generated when the X-ray pulse meets the particle (Loh et al., 2012). Aerodynamic lenses can also be used in the mass spectrometry of nano-mechanical resonators. They can achieve efficient transmission and focusing of large analytes without the need for ionization, significantly improving the performance of nano-mechanical mass spectrometers (Dominguez-Medina et al., 2018).

Although aerodynamic lenses have significant transmission effect on particles, the particle size range designed by most current aerodynamic lens is mainly within an order of magnitude, and the size range that can be focused is mainly below 3 μm (Fergenson et al., 2004; Srivastava et al., 2005; Tobias et al., 2006). Such as the 25-250 nm of Liu et al. (1995), the 100-900 nm and the 340-4000 nm of Schreiner et al. (1998; 1999), the 60-600 nm of Zhang et al. (2004), and the 125-600 nm of Zelenyuk et al. (2015). The particle size of aerosols in the atmosphere ranges from sub-nanometer to millimeter level, and focusing sample injection of particles with a wide particle size range is crucial for improving the analytical ability of aerosol mass spectrometry, such as the analysis of biological aerosols, dust, single cells.

Researchers have been working to expand the transmission range of particles by aerodynamic lenses. Research has shown that the focusing performance of aerodynamic lenses for small particles below 50 nm is limited by Brownian motion, while focusing on large particles is mainly affected by the larger inertia of particles (Wang et al., 2005; Wang and Mcmurry, 2006). At present, most of the reported aerodynamic lenses have low efficiency in transmitting large particle size (Cahill et al., 2014; Deng et al., 2008; Williams et al., 2013; Wu et al., 2009), so the key to achieving simultaneous transmission with a wide particle size range is to improve the focusing performance of large particles. The most direct method is to increase the stage number of lenses. For example, Lee et al.(2013) designed a seven-stage lens for particle detection in the range of 30 nm to 10 μm, but this study does not consider the impact of critical holes on the transmission loss of large particles and it is not applied in practice. Cahill et al. (2014) designed a high-pressure lens, and used a very long buffer chamber combined with a seven-stage lens to transmit 4-10 μm

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particles. However, experiments show that the transmission efficiency of 4 μm and 9 μm particles is only 20%, and the overall size of the lens system is relatively large. Increasing the stage number of lens is obviously beneficial for the transmission of wide-range particle size, but it can also lead to excessive volume of the injection system and increased assembly difficulty, as Liu et al. (2007) mentioned in the report that the beam focusing effect will decrease with the decrease in assembly accuracy of the aerodynamic lens system.

Hari et al. (2007) added a virtual impactor behind the critical hole, and their study shows that using the virtual impactor structure can reduce the cross trajectory phenomenon of large particles, which is beneficial for improving the transmission performance of large particles in the injection system. Chen et al. (2007) investigated the effect of the front and rear structure of critical hole on particle loss through numerical simulation and experimental verification, and optimized the structure to enhance the transmission efficiency of particles with 50nm and below, but the transmission range is not significantly extended. Liu et al. (2007) unified the inner diameter of the downstream pipeline of the critical hole to reduce the wall impingement loss of particles. Hwang et al. (2015) proposed a new type of critical hole, which can effectively reduce the incident angle of large particle beams through a converging-diverging structure design and achieve particle transmission in the range of 30 nm to 10 μm. However, the critical hole is difficult to fabricate due to the limitation of processing technology and has not been applied in practice. The above studies indicate that the large particles in the aerodynamic lens system loss on the surface of the critical hole. Du et al. (2023) proposed a pre-focus design for the first time to address the shortcomings of loss caused by large particles hitting the surface of the critical hole. A two-stage lens is added at the front of the critical hole, so that large particles could be focused on the axis to a greater extent before entering the critical hole. This design greatly reduces the beam incident angle of large particles in front of the critical hole, thereby reducing the impact loss of large particles on the surface of the critical hole. Combined with the seven-stage lens, efficient transmission of 62 nm-13 μm particles is achieved. However, due to the acceleration of particles after passing through the pre-focus lens, their downstream divergence angle after leaving the critical hole is large. Therefore, it is necessary to match a buffer chamber with a diameter of 250 mm to achieve efficient transmission of particles with a wide particle size range mentioned above. This design results in a very large overall size of the injection system, which is not conducive to the miniaturization of mass spectrometer.

This paper introduces a newly designed and manufactured small-volume pre-focus wide-range aerodynamic lens injection system (PFW-ALens) for transporting particles with diameters ranging from 100 nm to 10 μm. The key components of the injection system include a novel low-pressure loss pre-focus hole structure, a small buffer chamber and a five-stage aerodynamic lens group. Computational fluid dynamics software is used to model the transmission performance from the sampling inlet to the nozzle, and it is verified by experiments. Numerical simulation shows that the transmission efficiency of particles in the range of 100 nm-9 μm is higher than 90%.

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In experimental verification, the transmission efficiency of particles in the range of 100 nm-5 μm is above 90%, and the transmission efficiency of particles in the range of 9 μm and below is more than 50%. This lens system has great potential for application in bioaerosol analysis, sand and dust analysis, and miniaturization of mass spectrometer.

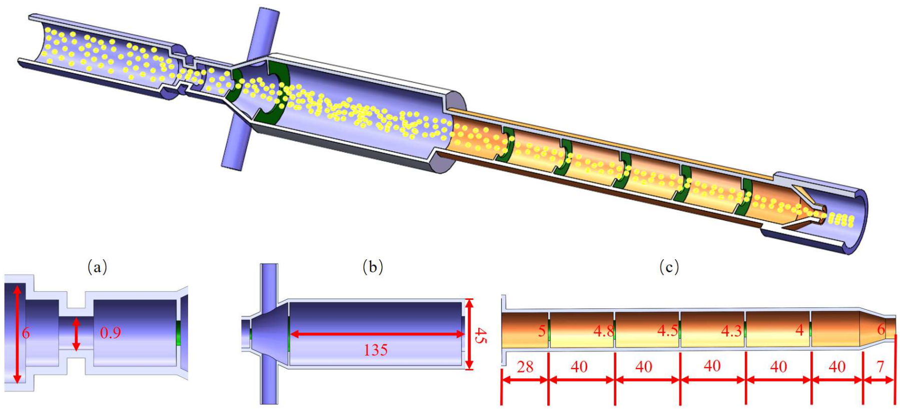

Fig. 1 Structural design of the injection system. Locally displayed are the pre-focus hole (a), buffer chamber (b), and aerodynamic lens system (c).

2 Numerical simulation and experimental design

2.1 Physical models

Fig. 1 shows the structure of the injection system, which consists of four modules, namely the pre-focus hole, the separation cone, the buffer chamber, and the aerodynamic five-stage lens group. Fig. 1(a ~ c) respectively represent the critical dimensions of each component. Aerosol particles approach the centerline through pre-focus holes, and a separation cone with diameter of 1mm and angle of 15° is set 1.6 mm downstream of the critical hole. The excess air between the critical hole and the separation cone is extracted by a side pump to achieve the concentration effect of aerosol particles, which then enter the buffer chamber. The particles accelerated through the critical hole gradually decelerate in the buffer chamber, and then are driven by the airflow into the aerodynamic lens system. The aerodynamic lens system consists of five apertures with diameters of 5 mm, 4.8 mm, 4.5 mm, 4.3 mm and 4 mm, respectively, and an accelerating nozzle with a diameter of 3 mm. The length from the inlet of the buffer chamber to the outlet of the acceleration nozzle is 370 mm, and the distance between the same components in the injection system designed by Du et al. is 570 mm. The aerodynamic lens system consisting of different diameters of apertures can effectively focus aerosol particles within a certain range onto the axis of the lens. Finally, aerosol particles are further accelerated by the action of the accelerating nozzle and enter the subsequent diameter measurement system.

2.2 Numerical model

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Ansys-Meshing is used to generate the mesh, and Fluent software is used to calculate the flow of gas and particle coupling between the sampling inlet and the accelerating nozzle. The pressure at the sampling inlet is set to 101325 Pa, the outlet pressure of the virtual impactor is set to 600 Pa, the buffer chamber and the aerodynamic lens group used are both set to operate in an environment below 300 Pa, and the pressure at the outlet of the accelerating nozzle is 0.1 Pa. The parameter settings are consistent with the study of Zhang et al. (2002). In addition, the Viscous model used in the simulation is laminar flow model. The discrete format of the flow equation is second-order upwind. The motion of aerosol particles will use the User Define Function (UDF) to load the particle resistance model and the Brownian force model. By setting the number, diameter, and release position of particles in the DPM model, the trajectory and velocity of particles can be obtained through cloud images.

2.3 Experimental exploration

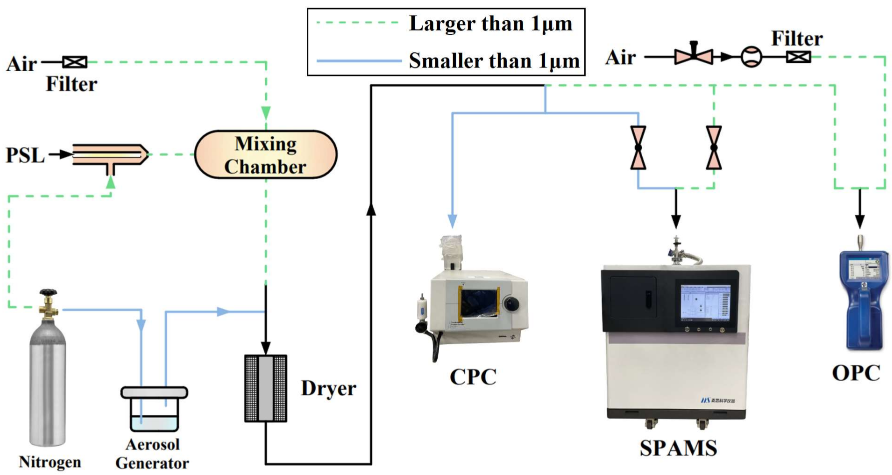

Fig. 2 Gas path connection in experiment

Standard polystyrene latex spheres (PSL, Thermo Fisher Scientific) ranging from 100 nm to 10 μm are used to characterize the focusing ability of aerodynamic lens system. The operation for generating and counting aerosols larger than 1 μm is as follows. First, the PSL solution is diluted with pure water, and then nitrogen is used as carrier gas to atomize the PSL solution using ICPMS atomizer before passing it into the mixing chamber, where the injection rates of PSL solution and nitrogen are 10 μL/min and 0.2 L/min, respectively. The excess moisture in the atomized aerosol particles is removed by heating the mixing chamber and introducing a drying tube, and then the aerosol particles are introduced into the optical particle counter (OPC, TSI, Model 9306) and SPAMS respectively through a three-way tube for counting. For particles below 1 μm, aerosol generator (TSI, Model 9302) is used to generate aerosols and condensed particle counter (CPC, TSI, Model 3775) is used for counting. The specific gas path connection is shown in Fig. 2, where the blue solid line is the test pipeline connection scheme for the transmission efficiency of

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particles below 1 μm, and the green dotted line represents the test pipeline connection scheme for the transmission efficiency of particles above 1 μm.

The single particle mass spectrometer used in this study is similar to HP-SPAMS (Du et al., 2024), but its optical system has been improved. The first diameter measuring laser is designed as a beam splitting optical structure similar to APS3321, and the dual beam can measure the aerodynamic diameter of particles. Photomultiplier tube PMT is used to detect the number of particles passing through the laser. In the experiment, we regard the total number of PMT detections obtained per unit time as the total number of particles entering SPAMS. For particles larger than 1 μm, the particle count of the corresponding size in OPC is taken as the total number of particles of that size, and the transmission efficiency of that particle size is the ratio of the total number of particles entering OPC and SPAMS, respectively. For particles below 1 μm, the transmission efficiency is the ratio of the particle concentration recorded by PMT to the particle concentration recorded by CPC.

3 Results and discussions

3.1 Aerodynamic lens with virtual impact

The basic model of aerodynamic lenses is consistent with that of Zhang et al. (2004), as shown in Fig. 3. Simulation results of Zhang et al. show that the focusing range of the lens of this size is mainly between 50 nm and 3 μm, and the transmission efficiency of 1.5 μm is 50%. The initial condition of this simulation is to assume that particles are uniformly distributed from the buffer chamber to the front of the lens, but in fact, for large particles, the state of entering the lens is not the same. Many scholars (Canagaratna et al., 2007; Drewnick et al., 2009; Meinen et al., 2010; Docherty et al., 2013;) have used this lens system to carry out different studies, and added a buffer chamber and a virtual impactor structure as shown in Fig. 1(a) on the basis of this model. By comparing the particle transmission efficiency curves before and after adding a virtual impactor, it can be found that after the addition of the virtual impactor (orange diamond symbol line), the focusing ability of the injection system for particles larger than 1 μm has increased to varying degrees, and the transmission efficiency of 7 μm particles has increased from the original 5% to 30%. Although the aerodynamic lens system with virtual impact structure has increased its ability to focus on large particles, this particle size range is still insufficient for the detection of large particle aerosols such as dust and organisms.

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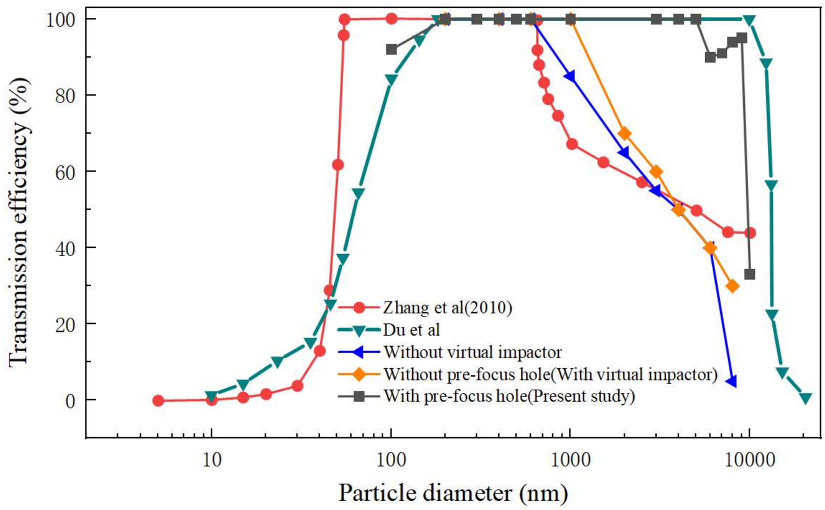

Fig. 3 Curves of particle focusing ability for different injection systems

3.2 Pre-focus injection system

In response to the shortcomings mentioned in section 3.1 regarding the transmission range of particles and the low transmission efficiency of larger particles, Du et al. pointed out that an important reason for the loss of large particles is that particles hit the surface of the critical hole to form the wall impingement loss. They proposed a pre-focus injection technique, which involves placing a set of two-stage lenses in the injection tube in front of the critical hole. The lenses can focus the particles to the axis in advance, avoiding the wall impingement loss of particles. This structure can reduce the loss of 10 μm particles from the original about 40% to 0. The curve in Fig. 3 shows that the seven-stage aerodynamic lens system with pre-focus structure designed by Du et al. can achieve efficient transmission in a wide particle size range of 0.18-10 μm. Although the lens of Du et al. can achieve a wide range, the overall lens system still has shortcomings. The main problem is that the particle beam diverges greatly after passing through the critical hole and virtual impact hole, so a large buffer with a diameter of 250 mm and a height of 250 mm is needed to release particles in the full particle size range. Combined with the seven-stage aerodynamic lens, the overall size and volume of the lens system can reach a diameter of 278 mm and a height of 875 mm. This is mainly because the design of the pre-focus lens produces a pressure loss, and the particles are focused on the central axis while also obtaining a large acceleration, which probably increases the divergence of the particles entering the strong buffer. As shown in Fig. 4, it can be found that the pre-focus structure makes the particles of different sizes accelerated compared with other systems. It can be found in Fig. 5(b) that the dispersion angle of 5 μm particles is also very large after leaving the critical hole, so a particularly large buffer chamber is needed to achieve particle collection and deceleration before entering the lens system to complete focusing. A large-size injection system is not only detrimental to the miniaturization of mass spectrometer, but also a

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seven-stage lens system can also lead to the increase of assembly accuracy, and the consistency of the lens is difficult to ensure.

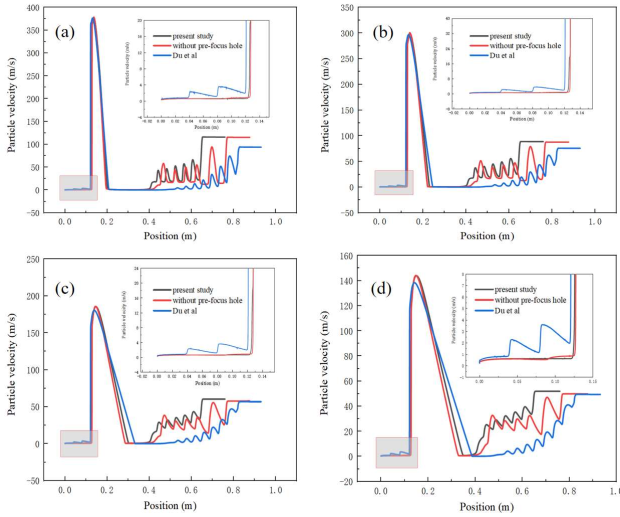

Fig. 4 Axial velocity of particles in different injection systems. (a) ~(d) represent particles of 0.5 μm, 1 μm, 3 μm, and 5 μm, respectively

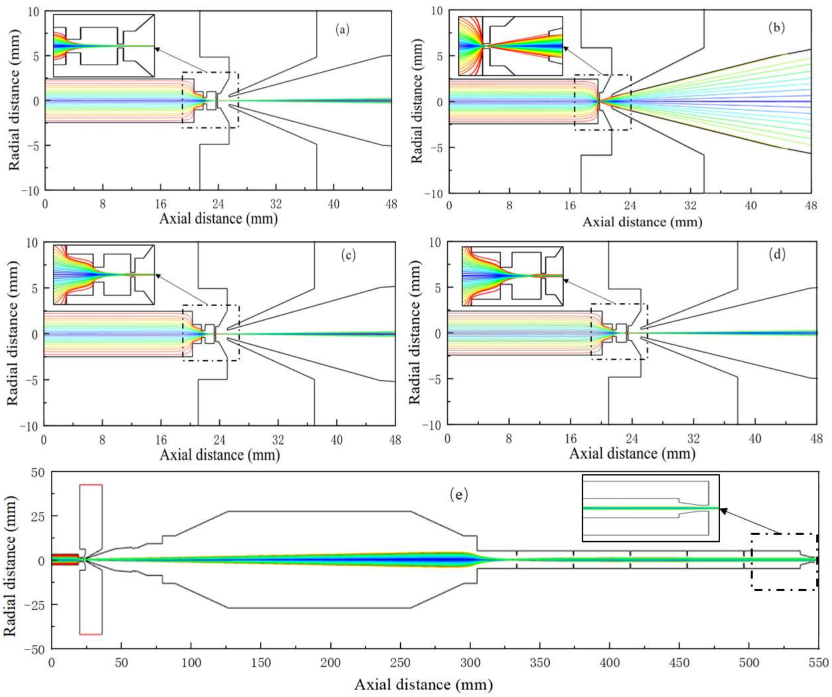

Fig. 5 Trajectories of large particles in different injection systems. (a) and (b) represent particle of 5 μm in the new and old systems, and (c) represents particle of 6 μm in the new system. (d) and (e) represent local and global trajectory of 8 μm

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3.3 New design

In this study, a new single-stage pre-focus structure is designed, which is equivalent to the critical hole as a two-stage lens. The specific structural dimensions are shown in Fig. 1. In the previous text, the pre-focus structure of Du will lead to particle acceleration and large dispersion angle, which will directly affect the size of the buffer chamber design and the focusing ability of the lens group. Therefore, the pressure drop of the pre-focus structure and the dispersion angle of particles are required in the design process. As shown in Fig. 4, the velocity distribution of 0.5 µm, 1 µm, 3 µm, and 5 µm particles under three different systems is compared. It can be found that the acceleration effect of particles in the pre-focus structure of Du is obvious, while the acceleration effect of the new pre-focus structure on particles is almost the same as that without the pre-focus structure. This means that the pre-focus hole used by PFW-ALens achieves pre-focus of large particles without additional acceleration effect on particles, which is more conducive to reducing the degree of change in the subsequent injection system. This also provides a good foundation for optimizing the length of the lens system and reducing the number of lenses.

The beam divergence angle of particles after passing through the critical hole directly affects the design of the buffer chamber and the transmission efficiency of particles (Lee et al., 2013). The greater the divergence degree, the easier it is for the particles to collide with the pipeline wall and cause losses. Therefore, the divergence angle after the critical hole determines the transmission range and efficiency of particles, especially for large particles. Fig. 5 shows the advantages of the new pre-focus structure for the transmission of large particles. Fig. 5a and Fig. 5b represent the transmission trajectories of 5 µm particles in PFW-ALens and the injection system without pre-focus holes, respectively. It can be observed that the divergence of particles after passing through the critical hole is much greater in the structure without pre-focus, so it is necessary to adapt to a larger buffer chamber. Even the buffer chamber structure used by the pre-focus lens structure of Du et al. reaches 250 mm * 250 mm. Fig. 5c and Fig. 5d show that even for larger particles of 6 µm and 8 µm, PFW-ALens can maintain a very small divergence angle. In fact, the structural size of the buffer chamber we used is 45 * 135 mm, and the volume of the buffer chamber is reduced by more than 90% compared to the previous one.

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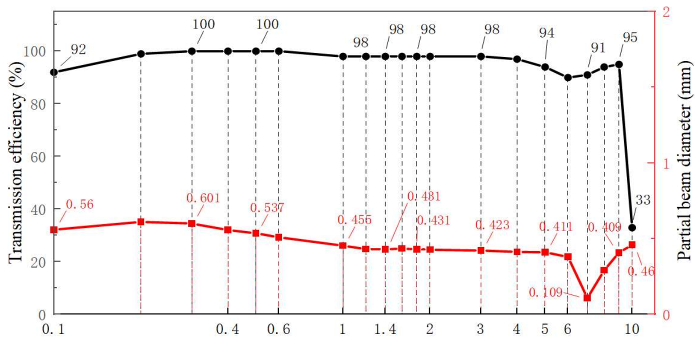

Fig. 6 Transmission efficiency and particle beam width of new injection system

The overall transmission characteristics of the lens model are simulated, and the transmission efficiency is obtained by calculating the ratio of the number of particles at the sampling inlet and the outlet of the nozzle. The beam width is obtained by exporting the radial distribution coordinates of particles 110 mm downstream of the nozzle using Fluent software and then calculating its 90% quantile. It can be seen from Fig. 6 that the particle transmission range of PFW-ALens is greatly increased, maintaining a transmission efficiency of over 90% for particles in the range of 100 nm to 9 μm, until the transmission efficiency of 10 μm particles shows a cliff-like decline. At the same time, the simulation results show that the beam width can be kept below 0.6 mm throughout the whole particle size transmission range. In fact, the transmission efficiency of 10 μm particles can be further increased by improving the structure. Simulation results show that increasing the length of the buffer chamber can greatly improve the above efficiency, so the efficient transmission of 9 μm is not the upper limit of this system. In general, the particle focusing ability exhibited by PFW-ALens in the range of 10 μm is almost consistent with the focusing performance of Du et al. in the same detection range. It is worth noting that the lens model used in this study is a PM2.5 five-stage lens, while most of the wide-range lenses generally use the structure of seven-stage lenses. This shows that the pre-focus device used in this study can not only focus large particles more effectively, but also accomplish focusing with fewer lenses, thereby reducing the volume of the injection system. This is of great significance for the miniaturization of high-performance single particle mass spectrometer.

3.4 Validation and application

Fig. 7 compares the transmission efficiency of particles with different particle sizes in numerical simulation and experimental validation of PFW-Alens. It can be found that the experimental verification results are basically in good agreement with the numerical simulation in the whole particle size range. The actual test of the transmission efficiency of 200 nm - 6 μm particles can be maintained at more than 90%, and the actual test of 100 nm particles can also reach more than 87%. In fact, 100nm particles will also cause some measurement loss due to the

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light scattering intensity. For particles with a particle size greater than 6 μm, the testing effect shows a significant decrease in efficiency, but 9 μm particles can still remain above 65%. The trend of 10 μm particles is consistent with the simulation results, with a transmission efficiency of only 25%. The decrease in efficiency of large particles may be attributed to inconsistent transmission losses of particles between OPC and B-SPAMS.

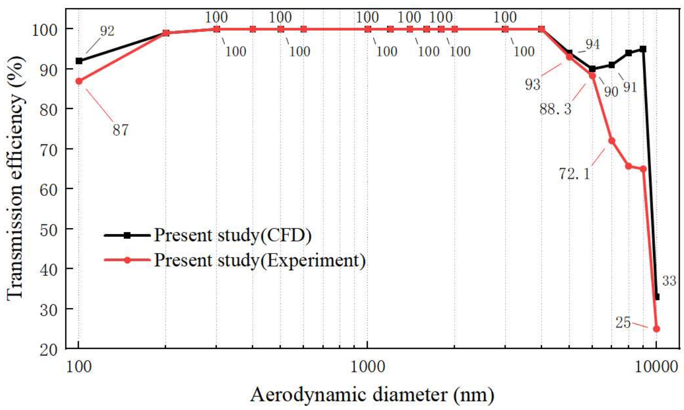

Fig. 7 Experimental verification of particle transmission

In order to characterize the analytical ability of PFW-ALens for large particles, the standard ULTRAFINE TEST DUST from Arizona is selected as the test sample. Firstly, APS is used to detect dust as a standard, and then PFW-ALens with pre-focus holes (red dotted line) and injection systems without pre-focus holes (black solid line) are used for testing and comparison. The specific particle size distribution is shown in Fig. 8, and the particle size distribution measured by PFW-ALens is closer to that measured by APS. The above experiments not only prove that PFW-ALens can more accurately detect the particle size distribution of dust compared to injection systems without pre-focus holes, but also prove that PFW-ALens can achieve efficient transmission of large particles, demonstrating the potential of new lens structure in detecting large particle analysis.

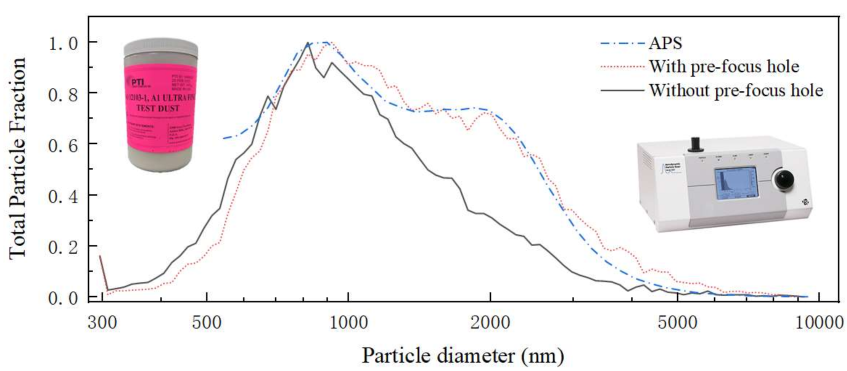

Fig. 8 Particle size distribution of standard dust in different injection systems

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5 Conclusions

In order to improve the transmission efficiency of large particles in the SPAMS injection system and reduce the volume of the injection system, this study developed an injection system PFW-ALens with the ability to focus large particles. This injection system adopts a new pre-focus structure, which can effectively reduce the size of buffer chamber and the number of lenses compared to the injection system with traditional pre-focus holes, while maintaining a low-loss transmission effect for particles with a larger particle size range. By adding a pre-focus structure, the focusing ability of the 2.5 μm lens system is significantly improved to 10 μm.

The numerical simulation results show that the newly designed injection system can achieve the focusing and transmission of particles with particle size ranging from 100 nm to 10 μm. Among them, the beam width of large particles after leaving the separation cone is significantly reduced compared to existing injection systems, which has extremely high particle transmission efficiency. The results show that the transmission efficiency can be higher than 90% when the particle size is less than 9 μm. Particles with a range of 200 nm-4 μm have a transmission efficiency of 100%. The injection system designed in this paper is currently the one that achieves the widest particle size range and highest transmission efficiency in the same structural size. This design is beneficial for further reducing the structural size of the injection system and the number of aerodynamic lenses, which provides ideas and inspiration for the miniaturization of the mass spectrometer.

Data availability. These data can be publicly accessible in free.

Author contributions. LL and ZXH designed the study; JHH and XL performed the simulations and experiments; JHH, LL, XL, ZXH and ZC participated in data analysis and result discussion; JHH and LL wrote the paper with the input from all authors.

Competing interests. The authors declare that they have no conflict of interest.

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References

Cahill, J. F., Darlington, T. K., Wang, X., Mayer, J., Spencer, M. T., Holecek, J. C., Reed, B. E., and Prather, K. A.: Development of a High-Pressure Aerodynamic Lens for Focusing Large Particles (4–10 μm) into the Aerosol Time-of-Flight Mass Spectrometer, Aerosol Science and Technology, 48, 948-956, 10.1080/02786826.2014.947400, 2014.

Canagaratna, M. R., Jayne, J. T., Jimenez, J. L., Allan, J. D., Alfarra, M. R., Zhang, Q., Onasch, T. B., Drewnick, F., Coe, H., Middlebrook, A., Delia, A., Williams, L. R., Trimborn, A. M., Northway, M. J., DeCarlo, P. F., Kolb, C. E., Davidovits, P., and Worsnop, D. R.: Chemical and microphysical characterization of ambient aerosols with the aerodyne aerosol mass spectrometer, Mass Spectrometry Reviews, 26, 185-222, 10.1002/mas.20115, 2007.

Chen, S.-C., Tsai, C.-J., Wu, C.-H., Pui, D. Y. H., Onischuk, A. A., and Karasev, V. V.: Particle loss in a critical orifice, Journal of Aerosol Science, 38, 935-949, 10.1016/j.jaerosci.2007.06.010, 2007.

Clemen, H.-C., Schneider, J., Klimach, T., Helleis, F., Köllner, F., Hünig, A., Rubach, F., Mertes, S., Wex, H., Stratmann, F., Welti, A., Kohl, R., Frank, F., and Borrmann, S.: Optimizing the detection, ablation, and ion extraction efficiency of a single-particle laser ablation mass spectrometer for application in environments with low aerosol particle concentrations, Atmospheric Measurement Techniques, 13, 5923-5953, 10.5194/amt-13-5923-2020, 2020.

Deng, R., Zhang, X., Smith, K. A., Wormhoudt, J., Lewis, D. K., and Freedman, A.: Focusing Particles with Diameters of 1 to 10 Microns into Beams at Atmospheric Pressure, Aerosol Science and Technology, 42, 899-915, 10.1080/02786820802360674, 2008.

Docherty, K. S., Jaoui, M., Corse, E., Jimenez, J. L., Offenberg, J. H., Lewandowski, M., and Kleindienst, T. E.: Collection Efficiency of the Aerosol Mass Spectrometer for Chamber-Generated Secondary Organic Aerosols, Aerosol Science and Technology, 47, 294-309, 10.1080/02786826.2012.752572, 2013.

Dominguez-Medina, S., Fostner, S., Defoort, M., Sansa, M., Stark, A.-K., Halim, M. A., Vernhes, E., Gely, M., Jourdan, G., Alava, T., Boulanger, P., Masselon, C., and Hentz, S.: Neutral mass spectrometry of virus capsids above 100 megadaltons with nanomechanical resonators, Science, 362, 918-922, 10.1126/science.aat6457, 2018.

Drewnick, F., Hings, S. S., Alfarra, M. R., Prevot, A. S. H., and Borrmann, S.: Aerosol quantification with the Aerodyne Aerosol Mass Spectrometer: detection limits and ionizer background effects, Atmos. Meas. Tech., 2, 33-46, 10.5194/amt-2-33-2009, 2009.

Du, X., Zhuo, Z., Li, X., Li, X., Li, M., Yang, J., Zhou, Z., Gao, W., Huang, Z., and Li, L.: Design and Simulation of Aerosol Inlet System for Particulate Matter with a Wide Size Range, Atmosphere, 14, 10.3390/atmos14040664, 2023.

Du, X., Xie, Q., Huang, Q., Li, X., Yang, J., Hou, Z., Wang, J., Li, X., Zhou, Z., Huang, Z., Gao, W., and Li, L.: Development and characterization of a high-performance single-particle aerosol mass spectrometer (HP-SPAMS), Atmos. Meas. Tech., 17, 1037-1050, 10.5194/amt-17-1037-

2024, 2024.

Fergenson, D. P., Pitesky, M. E., Tobias, H. J., Steele, P. T., Czerwieniec, G. A., Russell, S. C., Lebrilla, C. B., Horn, J. M., Coffee, K. R., Srivastava, A., Pillai, S. P., Shih, M.-T. P., Hall, H. L., Ramponi, A. J., Chang, J. T., Langlois, R. G., Estacio, P. L., Hadley, R. T., Frank, M., and Gard, E. E.: Reagentless Detection and Classification of Individual Bioaerosol Particles in Seconds, Analytical Chemistry, 76, 373-378, 10.1021/ac034467e, 2004.

Hari, S., McFarland, A. R., and Hassan, Y. A.: CFD Study on the Effects of the Large Particle Crossing Trajectory Phenomenon on Virtual Impactor Performance, Aerosol Science and Technology, 41, 1040-1048, 10.1080/02786820701697549, 2007.

Hwang, T.-H., Kim, S.-H., Kim, S. H., and Lee, D.: Reducing particle loss in a critical orifice and an aerodynamic lens for focusing aerosol particles in a wide size range of 30 nm — 10 μm, Journal of Mechanical Science and Technology, 29, 317-323, 10.1007/s12206-014-1238-4, 2015.

Lee, K.-S., Hwang, T.-H., Kim, S.-H., Kim, S. H., and Lee, D.: Numerical Simulations on Aerodynamic Focusing of Particles in a Wide Size Range of 30 nm–10 μm, Aerosol Science and Technology, 47, 1001-1008, 10.1080/02786826.2013.808737, 2013.

Liu, P., Ziemann, P. J., Kittelson, D. B., and McMurry, P. H.: Generating Particle Beams of Controlled Dimensions and Divergence: II. Experimental Evaluation of Particle Motion in Aerodynamic Lenses and Nozzle Expansions, Aerosol Science and Technology, 22, 314-324, 10.1080/02786829408959749, 1995.

Liu, P. S. K., Deng, R., Smith, K. A., Williams, L. R., Jayne, J. T., Canagaratna, M. R., Moore, K., Onasch, T. B., Worsnop, D. R., and Deshler, T.: Transmission Efficiency of an Aerodynamic Focusing Lens System: Comparison of Model Calculations and Laboratory Measurements for the Aerodyne Aerosol Mass Spectrometer, Aerosol Science and Technology, 41, 721-733, 10.1080/02786820701422278, 2007.

Loh, N. D., Hampton, C. Y., Martin, A. V., Starodub, D., Sierra, R. G., Barty, A., Aquila, A., Schulz, J., Lomb, L., Steinbrener, J., Shoeman, R. L., Kassemeyer, S., Bostedt, C., Bozek, J., Epp, S. W., Erk, B., Hartmann, R., Rolles, D., Rudenko, A., Rudek, B., Foucar, L., Kimmel, N., Weidenspointner, G., Hauser, G., Holl, P., Pedersoli, E., Liang, M., Hunter, M. S., Gumprecht, L., Coppola, N., Wunderer, C., Graafsma, H., Maia, F. R. N. C., Ekeberg, T., Hantke, M., Fleckenstein, H., Hirsemann, H., Nass, K., White, T. A., Tobias, H. J., Farquar, G. R., Benner, W. H., Hau-Riege, S. P., Reich, C., Hartmann, A., Soltau, H., Marchesini, S., Bajt, S., Barthelmess, M., Bucksbaum, P., Hodgson, K. O., Strüder, L., Ullrich, J., Frank, M., Schlichting, I., Chapman, H. N., and Bogan, M. J.: Fractal morphology, imaging and mass spectrometry of single aerosol particles in flight, Nature, 486, 513-517, 10.1038/nature11222, 2012.

Meinen, J., Khasminskaya, S., Rühl, E., Baumann, W., and Leisner, T.: The TRAPS Apparatus:

https://doi.org/10.5194/egusphere-2024-2577
Preprint. Discussion started: 1 October 2024

Enhancing Target Density of Nanoparticle Beams in Vacuum for X-ray and Optical Spectroscopy, Aerosol Science and Technology, 44, 316-328, 10.1080/02786821003639692, 2010.

Murphy, D. M., Cziczo, D. J., Froyd, K. D., Hudson, P. K., Matthew, B. M., Middlebrook, A. M., Peltier, R. E., Sullivan, A., Thomson, D. S., and Weber, R. J.: Single-particle mass spectrometry of tropospheric aerosol particles, Journal of Geophysical Research: Atmospheres, 111, 10.1029/2006jd007340, 2006.

Peck, J., Gonzalez, L. A., Williams, L. R., Xu, W., Croteau, P. L., Timko, M. T., Jayne, J. T., Worsnop, D. R., Miake-Lye, R. C., and Smith, K. A.: Development of an aerosol mass spectrometer lens system for PM2.5, Aerosol Science and Technology, 50, 781-789, 10.1080/02786826.2016.1190444, 2016.

Schreiner, J., Schild, U., Voigt, C., and Mauersberger, K.: Focusing of Aerosols into a Particle Beam at Pressures from 10 to 150 Torr, Aerosol Science and Technology, 31, 373-382, 10.1080/027868299304093, 1999.

Schreiner, J., Voigt, C., Mauersberger, K., McMurry, P., and Ziemann, P.: Aerodynamic Lens System for Producing Particle Beams at Stratospheric Pressures, Aerosol Science and Technology, 29, 50-56, 10.1080/02786829808965550, 1998.

Srivastava, A., Pitesky, M. E., Steele, P. T., Tobias, H. J., Fergenson, D. P., Horn, J. M., Russell, S. C., Czerwieniec, G. A., Lebrilla, C. B., Gard, E. E., and Frank, M.: Comprehensive Assignment of Mass Spectral Signatures from Individual Bacillus atrophaeus Spores in Matrix-Free Laser Desorption/Ionization Bioaerosol Mass Spectrometry, Analytical Chemistry, 77, 3315-3323, 10.1021/ac048298p, 2005.

Tobias, H. J., Pitesky, M. E., Fergenson, D. P., Steele, P. T., Horn, J., Frank, M., and Gard, E. E.: Following the biochemical and morphological changes of Bacillus atrophaeus cells during the sporulation process using Bioaerosol Mass Spectrometry, Journal of Microbiological Methods, 67, 56-63, 10.1016/j.mimet.2006.03.001, 2006.

Wang, X. and McMurry, P. H.: An experimental study of nanoparticle focusing with aerodynamic lenses, International Journal of Mass Spectrometry, 258, 30-36, 10.1016/j.ijms.2006.06.008, 2006.

Wang, X., Kruis, F. E., and McMurry, P. H.: Aerodynamic Focusing of Nanoparticles: I. Guidelines for Designing Aerodynamic Lenses for Nanoparticles, Aerosol Science and Technology, 39, 611-623, 10.1080/02786820500181901, 2005.

Williams, L. R., Gonzalez, L. A., Peck, J., Trimborn, D., McInnis, J., Farrar, M. R., Moore, K. D., Jayne, J. T., Robinson, W. A., Lewis, D. K., Onasch, T. B., Canagaratna, M. R., Trimborn, A., Timko, M. T., Magoon, G., Deng, R., Tang, D., de la Rosa Blanco, E., Prévôt, A. S. H., Smith, K. A., and Worsnop, D. R.: Characterization of an aerodynamic lens for transmitting particles

https://doi.org/10.5194/egusphere-2024-2577
Preprint. Discussion started: 1 October 2024

greater than 1 micrometer in diameter into the Aerodyne aerosol mass spectrometer, Atmospheric Measurement Techniques, 6, 3271-3280, 10.5194/amt-6-3271-2013, 2013.

Wu, X., Omenetto, N., and Winefordner, J. D.: Development, Characterization, and Application of a Versatile Single Particle Detection Apparatus for Time-Integrated and Time-Resolved Fluorescence Measurements—Part I: Theoretical Considerations, Laser Chemistry, 2009, 1-10, 10.1155/2009/295765, 2009.

Zelenyuk, A., Imre, D., Wilson, J., Zhang, Z., Wang, J., and Mueller, K.: Airborne Single Particle Mass Spectrometers (SPLAT II & miniSPLAT) and New Software for Data Visualization and Analysis in a Geo-Spatial Context, Journal of the American Society for Mass Spectrometry, 26, 257-270, 10.1007/s13361-014-1043-4, 2015.

Zhang, X., Smith, K. A., Worsnop, D. R., Jimenez, J., Jayne, J. T., and Kolb, C. E.: A Numerical Characterization of Particle Beam Collimation by an Aerodynamic Lens-Nozzle System: Part I. An Individual Lens or Nozzle, Aerosol Science and Technology, 36, 617-631, 10.1080/02786820252883856, 2002.

Zhang, X., Smith, K. A., Worsnop, D. R., Jimenez, J. L., Jayne, J. T., Kolb, C. E., Morris, J., and Davidovits, P.: Numerical Characterization of Particle Beam Collimation: Part II Integrated Aerodynamic-Lens–Nozzle System, Aerosol Science and Technology, 38, 619-638, 10.1080/02786820490479833, 2004.