Design and Simulation of Virtual Impact Sampler of 5um Particle Size

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***Abstract*—**A virtual impactor of 5 micrometer cut-off particle size is designed based on inertial impact theory for the capture of microbial aerosol particles diffused in the air. then the flow field characteristics of virtual impactor are simulated by using the professional simulation software FLUENT and the performance of capture and separation was verified by the simulation results.

Keywords*—Inertial impact; Virtual impact; Aerosol; Separation particle size*

I. INTRODUCTION

It is very important to make a effective screening for the determination of aerosol whether it is the aerosol existing in the natural environment or the artificial aerosol used as the detection medium. At present, many technologies are used to separate the particle dispersion in aerosol according to the particle size such as inertial impact, gravity sedimentation, centrifugal sedimentation and thermal sedimentation. Inertial impact technology is widely used because of its simple structure and easy implementation.

With the change of the particle separation size of aerosol, virtual impact technology, as a branch of inertial impact technology, has been developed gradually. The concept of virtual impact was first proposed by Hounam in 1965. The phenomenon of virtual impact was found in the experiment of air particle collection by busing multistage cascade centrifugal separator. Then William and Conner found that the separation efficiency curve of the virtual impactor is S-shaped rather than ideal vertical line after analyzing the influencing factors of the virtual impactor[1]. In 1980, Marple obtained the theoretical relationship between Reynolds number, minor flow ratio, structure parameters and separation efficiency of the virtual impactor nozzle by solving the equations of flow filed and particle motion[2]. The 80's and 90's of the 20th century are the fastest developing period of virtual impactor. Marple , Loo and Szymanski have made breakthroughs in the research of multi nozzle with large flow, single nozzle with small flow and high efficiency and multi-stage multi nozzle respectively[3]. Virtual impactor have a good separation effect for particles smaller than 10 micrometer, it can be used in aerosol simpler, particle separation classifier, aerosol generator, aerodynamic particle size measurement and so on[4,5]. In addition, the virtual impactor also plays an important role in the evaluation of laboratory aerosol and microbial aerosol[6,7].

II. VIRTUAL IMPACT THEORY

The key components of virtual impactor simpler generally include nozzle and receiver, and its working principle is shown in Figure 1.

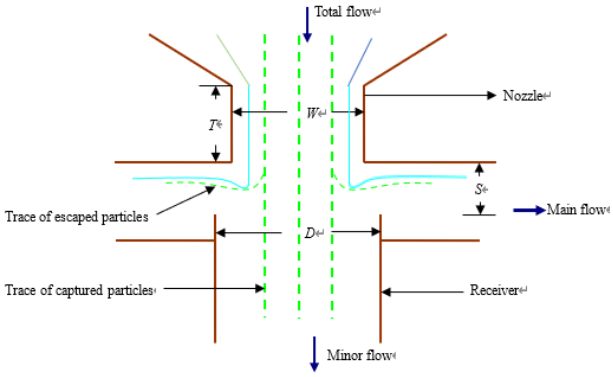

Fig. 1. Basic principle of virtual impactor simpler

As shown in Figure 1, the aerosol flow is accelerated due to the decrease of the nozzle diameter when it passes through the nozzle under the action of sampling power. The larger particles in the aerosol have strong ability to keep trajectory because of their large inertial, so they enter the receiver with the minor flow. The smaller particles in the aerosol have smaller inertial and weak ability to keep the original trajectory, and escape with the main flow.

When the total flow rate is Q(L/min) and the separation particle size is d_{50}(aerodynamic diameter of particle with 50% collection efficiency, unit: um), the diameter of nozzle is assumed to be W, the diameter of receiver is D, the distance between receiver and nozzle is S, the length of acceleration section is T, the minor flow rate is Q_1 and the main flow rate is Q_2. The collection efficiency curve is shown in Figure 2.

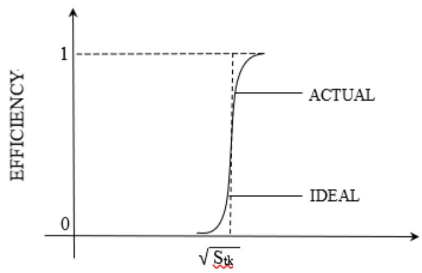

Fig. 2. Collection efficiency curve of virtual impactor

According to Marple's design theory of virtual impactor[8] the flow filed characteristic between nozzle and receiver can be reflected by stokes number S_{tk50}. S_{tk50} is the Stokes number when the collection efficiency is 50%.

$$S_{tk50} = \frac{\rho \cdot C \cdot V \cdot d_{50}^{\ 2} \cdot /18\mu}{W/2} \tag{1}$$

where: ρ is the density of aerosol particle, the value can be taken as 1 when d_{50} is aerodynamic size. C is the Cunningham slip correction factor. V is the mean velocity at the nozzle. μ is the fluid viscosity. In addition, the velocity V can be obtained from the following equation.

$$V = \frac{4Q}{\pi W^2} \qquad (2)$$

In virtual impactor, stokes number can be defined as the ratio of the particle stopping distance to the radius of the nozzle.

According to Eq(1), the expression of nozzle diameter W can be obtained

$$W = \sqrt[3]{\frac{4 \cdot \rho \cdot C \cdot d_{50}^{2} \cdot Q}{9 \cdot N \cdot \pi \cdot \mu \cdot S_{tk50}}} \qquad (3)$$

Where N is the number of nozzle.

It should be noted that for the convenience of calculation, the unit in the Eq(3) correspond to centimeter.

III. Discussion on the Value of Calculation Parameters

The key parameters affecting the accuracy of the calculation results in Eq(1) are Stokes number S_{tk}, which should be determined artificially according to the experimental curve and experience, and the Reynolds number Re related to S_{tk}.

A. Reynolds number Re

In the virtual impactor, the Reynolds number abide by the following equation.

$$Re = \frac{4\rho_g Q}{\pi \mu W} \qquad (4)$$

Where: ρ_g is the density of atmosphere, the value is 1.192×10^{-3}g/cm^3 under the condition 20°C and 101kPa.

Equation (4) is usually used to verify whether the Re calculation result is in the range of values after the nozzle diameter is determined. The relationship between Re and S_{tk} is shown Figure 3.

Relevant experiments show that the T/W of the single-stage virtual impactor is between 1.0 and 1.5, the S/W of the single-stage virtual impactor is between 1.2 and 1.5, the Reynolds number is between 500 and 3000 and the minor flow ratio Q_1/Q is more than 10%.

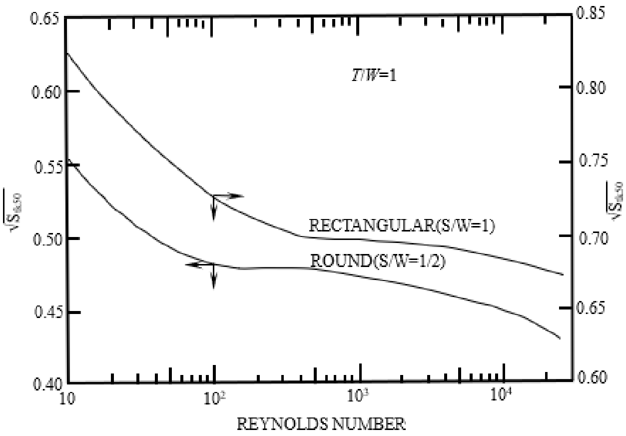

Fig. 3. Relationship between Re and S_{tk50}

B. Stokes number S_{tk50}

After determining the Reynolds number and the value of S/W, refer to the minor flow ratio Q_1/Q, Stokes number can be selected according to Figure 3 and the collection efficiency curve of conventional impactor in Figure 4.

The nozzle diameter can be obtained by substituting the selected Stokes number into Eq(3). For the convenience of design, the nozzle diameter can be properly rounded.

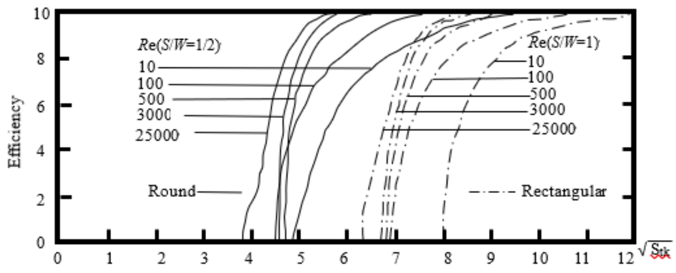

Fig. 4. Collection efficiency curve of conventional impactor

C. The diameter of receiver D

The diameter of receiver is generally 1.3-1.4 times of the nozzle diameter.

D. The distance between nozzle and receiver S

The distance between nozzle and receiver should be larger than nozzle diameter, it is recommended to select 1.2-1.5 times nozzle diameter.

E. The length of acceleration section T

The length of the accelerating section of the nozzle can be selected as one time of the nozzle diameter.

In addition, in order to avoid the adsorption loss of particles, the length of nozzle protruding from the nozzle plate should be 2-3times of the nozzle diameter.

IV. Design and Simulation of 5um Microbial Aerosol Sampler

The design goal is to capture microbial aerosol particles with particle size greater than 5um at a total flow rate of 100L/min.

The value of parameters in Eq(3) are shown in the Table I.

TABLE I. VALUE OF KEY PARAMETER

Parameter	**ρ**(g/cm^3)	**C**	**d_{50}**(cm)	**Q**(cm^3/s)	**μ**(P)	**S_{tk50}**
Value	1	1	5*10^{-4}	1667	1.81*10^{-6}	0.67^2

According to the Fig.3 and Fig.4, the Reynolds number is selected between 3000 and 25000, so the corresponding Stokes number S_{tk50} is about 0.67^2.

A. Calculation results and verification

By substituting the values of each parameter into Eq(3), the diameter of the nozzle is about 7.6mm, and the rounded value is 7.5mm. According to the discussion of structure parameters, the receiver diameter is about 9.5mm, the length of the acceleration section is 7.5mm, and the distance between the nozzle and receiver is about 11.5mm.

After obtaining the structural parameters of the sampler, the corresponding Reynolds number Re1 under the structure and working condition can be calculated according to Eq(4). If the result value is between the estimated value range of 3000-25000, the Stokes number value is proved valid, which further shows that the calculation process and results of the structural parameter of the virtual impactor are reasonable.

After substituting nozzle diameter and working condition parameters into Eq(4), the calculation result is $R_{e1}\approx18390$, which proves that the value of nozzle diameter is reasonable.

B. Simulation of virtual impactor

According to the calculated structure parameters, a virtual impactor which meets the use requirements and is easy to process is designed, and its structure is shown in the Figure 5.

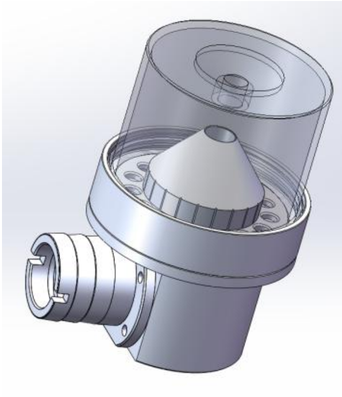

Fig. 5. Structure diagram of virtual impactor

In order to verify the sampling performance and collection performance of aerosol particles of the virtual impactor, based on the actual working parameters and the simplified 3D model, the fluid simulation was carried out by using the FLUENT module of ANSYS software. Figure 6 is the simplified model of virtual impactor applied to fluid simulation.

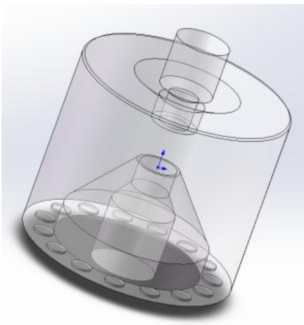

Fig. 6. The simplified model for simulation

For the sake of the high efficiency of simulation calculation and the retionality of flow field setting, the simplified model only involves the aerosol inlet, outlet and the area which particles are separated.

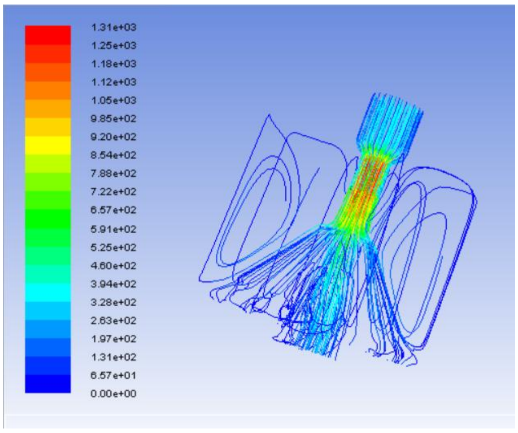

Fig. 7. Simulated trace of 5um particles

It can be seen from Fig.7 that most of the 5um aerosol particles entering the receiver of virtual impactor, and only a small number of particles escape to the surrounding pores. The above simulation results shows that the parameter calculation and structure design of the virtual impactor are reasonable and effective.

CONCLUSION

Based on the principle of virtual impact, this paper deduced the calculation formula of nozzle diameter and gave the key structure parameters of the virtual impactor to capture microbial aerosol particles larger than 5um combined with the actual requirement and working condition. Then according to these parameters, a virtual impactor with complete structure is designed and the flow filed performance is simulated. The simulation results show that the capture efficiency of the virtual impactor designed in this paper is more than 50%, which proves the rationality of the calculation process and the effectiveness of the sampler performance.

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