Experimental Characterization of Aerosol Suspension in a Rotating Drum

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Abstract

Rotating drum chambers are simple and effective devices for retaining particles in airborne state for prolonged periods. Many studies including inhalation toxicology, environmental fate, and survivability of airborne pathogens could benefit from using them. Particle size is the major factor governing aerosol suspension. Yet reliable experimental data as a function of particle size on the optimal rotation rate are limited. Therefore, this study aims to experimentally characterize a rotating drum and to optimize the operation rate for the bioaerosol size spectrum. Moreover, the sampling methodology for evaluating the performance of a rotating drum is also investigated. Charge-neutralized potassium sodium tartrate (PST) particles generated by an ultrasonic atomizer are used as surrogates of bioaerosols to characterize the performance of the rotating drum. Aerosol number concentrations and size distributions in the rotating drum are continuously or intermittently measured by an aerodynamic particle sizer (APS) in real time. Then the decay constants of aerosol number concentrations as a function of particle size, elapsed time, and rotation rate are calculated, respectively. Experimental results revealed that the rotation of a drum chamber enhances particle suspension greatly and the rotating rate can be optimized to retain the suspended particles for an extended time period. With the current drum geometry, the optimal rotation rate varies from 2 to 7 rpm in the particle size range of 1 to 7 μm and is proportional to particle size. When operating at the optimal rotation rate (2-4 rpm), 5% of 1-μm particles can remain suspended for over 24 hours. However, it is crucial to adjust the optimal rate carefully for large particles and long suspension duration.

Keywords: Rotating drum, Decay constant, Suspension time, Optimal rotating rate

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INTRODUCTION

Many infectious organisms including viruses, bacteria, and fungi have been shown to be transmitted by the airborne route. The ability of these microorganisms to survive in airborne state plays a key role in their aerial dissemination. Therefore, besides recommending good personal hygiene practices, many researchers tried to formulate environmental control guidelines through investigating the effects of factors such as temperature, relative humidity, and light or chemicals exposure on promoting or retarding the survival of infectious organisms in the air. However, results on airborne survival of microorganisms from previous studies varied considerably due to different experimental techniques used. Thus, a well-characterized experimental system is essential for making generalized conclusions and developing mathematical models.

Many measures have been developed to control the infectiveness of airborne pathogens (Huang et al., 2012; Chen et al., 2016). The key to validate the effectiveness of control measures is to retain the microorganisms in aerosol phase for prolonged periods of time. However, the suspension of bioaerosols is subjected to gravitational settling in a stationary test chamber. Although keeping the aerosols in stationary chambers with gently stirring would delay sedimentation, large particles still need long settling distances to extend the airborne period. Alternatively, a rotating drum (Goldberg et al., 1958), which is an uncomplicated but more effective device, was shown to be capable of retaining particles in airborne state for prolonged periods. Experimentally, as compared with a stirred settling aerosol chamber 1 m in height, almost a 20-fold increase in duration of holding time for 1-μm particles in a 1-m-diameter drum chamber rotated at 2 rpm is demonstrated (Goldberg, 1971). Another subsequent study generated Di-n-hexyl phthalate (DHP) particles with a 0.8-μm mass median diameter in a 40-cm-diameter drum and found a 90% reduction of the particle settling loss as the drum rotated at about 3 rpm (Frostling, 1973). However, bacterial and fungal aerosols in indoor environment are usually in the

size range of 3 μm in count median diameter (CMD) which is much larger than those tested in the previous studies (Kuo, 2015). Even though the aerosol decay as a function of particle size in a rotating drum chamber has been comprehensively studied using advanced particle sizing instruments (Embury and Sutton, 2005; Sutton, 2005), several issues that can affect the results have not been addressed. Since aerosol charge neutralizers were not used, their data would reflect the influence of particle charge. Furthermore, the high particle number concentrations used in these studies might cause significant coincidence errors in the APS counts.

In rotating drum chambers, particles remain suspended as a result of the competition between gravitational and centrifugal forces. At high drum rotation rate, the centrifugal force is the dominant aerosol deposition mechanism. Taking into account the combined effects of gravitational and centrifugal forces, Gruel et al. (1987) developed an equation to predict the fraction of suspended particles by assuming that the aerosols in the rotating chamber decay exponentially (referred to as Gruel's model). The fraction of suspended particles is

$$\frac{N}{N_0} = \left[\frac{(R-r_0)^2}{R^2}\right] \exp(-2\tau\omega^2 t) \quad (1)$$

where N and N_0 are number of particles and initial number of particles in drum, respectively; R is the drum radius; r_0 is the radius of gyration of a particle in the rotating drum ($r_0 = \tau g/\omega$); τ, g and ω are the particle relaxation time, gravitational acceleration and angular velocity of drum rotation, respectively; and t is the time beginning after one revolution.

Gruel's model is appropriate for predicting the fraction of suspended particles after one revolution when centrifugal force is much less than gravitational force (Embury and Sutton, 2005). However, it is not applicable when the rotation rate is reduced to zero because the solution does not converge to the gravitational settling solution (Asgharian and Moss, 1992). Therefore, Asgharian and Moss (1992) used the concept of limiting trajectories of the suspended particles

that proposed by Pich (1972) to predict the fraction of suspended particles as a result of the combined effects of gravity and centrifugation over the complete range of rotation rates (referred to as Moss's model). The fraction of suspended particles is

$$\frac{N}{N_0} = 1 - \frac{1}{\pi}\left[\frac{y_p}{R}\sqrt{1-\left(\frac{y_p}{2R}\right)^2} + 2sin^{-1}\frac{y_p}{2R}\right] \quad \text{for 0 rpm} \tag{2}$$

$$\frac{N}{N_0} = exp(-2\tau\omega^2 t) \quad \text{for } \frac{H}{R} \le 1 - \exp(-\tau\omega^2 t) \tag{3}$$

$$\frac{N}{N0} = \frac{1+\exp(-2\tau\omega^2 t)}{2} - \frac{1}{\pi}\left[\frac{H_1}{R}\sqrt{1-\left(\frac{H_1}{R}\right)^2} + sin^{-1}\frac{H_1}{R} + \frac{H_2}{R}\sqrt{\exp(-2\tau\omega^2 t) - \left(\frac{H_2}{R}\right)^2} + \exp(-2\tau\omega^2 t)sin^{-1}\left(\frac{H_2}{R}\right)\right]$$

$$\text{for } 1 - \exp(-\tau\omega^2 t) \le \frac{H}{R} \le 1 + \exp(-\tau\omega^2 t) \tag{4}$$

$$\frac{N}{N_0} = 0 \quad \text{for } \frac{H}{R} \ge 1 + \exp(-\tau\omega^2 t) \tag{5}$$

where

$$y_p = \tau g t - \tau^2 g\left(1 - exp^{-t/\tau}\right)$$

$$\mathrm{H} = \frac{\tau g}{\omega}\sqrt{1 - 2\cos(\omega t)\exp(-\tau\omega^2 t) + \exp(-2\tau\omega^2 t)} \quad \text{for } \omega t < \pi$$

$$\mathrm{H} = \frac{\tau g}{\omega}[1 + \exp(-\tau\omega^2 t)] \quad \text{for } \omega t > \pi$$

$$H_1 = \frac{R^2 + H^2 - R^2 exp(-2\tau\omega^2 t)}{2H}$$

$$H_2 = H - H_1$$

and t here is the time begins as the first revolution begins. It should be noted that the parameter "time" in Moss's equation is different from that defined in Gruel's equation (or Eq. (1)).

The rotating drum has been extensively employed to study the retention of microorganisms in aerosol phase and the decay of bioaerosols under a variety of environmental conditions, such as relative humidity, temperature, UV, ozone, germicides, gaseous pollutants and so forth. (Krumins et al., 2008; Verreault et al., 2008; Piercy et al., 2010; Santarpia et al., 2012; Verreault et al., 2013; Santarpia et al., 2014; Verreault et al., 2014; Ratnesar-Shumate et al., 2015; Johnson et al., 2016; Turgeon et al., 2016; Haddrell and Thomas, 2017). However, the bioaerosol decay measured in these studies is a combination of biological decay and physical decay. It is important to evaluate the physical decay of aerosols in a rotating drum so as to elucidate the actual effectiveness of the studied parameters. Moreover, the deposition of aerosols is a function of particle size and it is crucial to characterize the physical decay for the bioaerosol size spectrum in a rotating chamber to optimize the rotation rate for prolonged aerosol suspension time period.

An endeavor has been made to experimentally investigate the aerosol physical decay as a function of particle size, suspension time and rotation rate in a rotating chamber by Sutton and colleague (Embury and Sutton, 2005; Sutton, 2005). The aerosol decay experiments are conducted in a 1-m-diameter drum chamber with a piston inside the drum to pull air into or out of the drum which is different from Goldberg's rotating drum. However, some of the experimental results reveal a need for further improvements. First, the test particles failed to show a bimodal distribution with peaks at 3 and 6 μm as expected due to triboelectric charging. The test particles were generated pneumatically in a large plastic bag using a sonic nozzle. The size distribution and concentration of challenged aerosols are not well controlled to minimize the measurement bias. Moreover, some experimental data are not reasonable. For example, the aerosol decay results of 3 rpm test did not fall in line with those of 2 and 4 rpm tests and the concentrations of 1- and 2-μm particles increased within the first 4 to 6 hours for some of the tests. These

discrepancies have not been addressed. Finally, Sutton's experimental measurements and Moss's model agreed only qualitatively but not quantitatively.

In this study, some improvements have been made to obtain reliable measurement data. The test aerosols were generated and neutralized before introduced into the drum chamber to eliminate the measurement bias due to triboelectric charging. Furthermore, the initial aerosol concentration in the rotating drum was well controlled at a low concentration (approximately 170 particles/cm^3) to reduce aerosol coagulation. The size distribution of the test aerosols meets the designate size range of different types of bioaerosols. To make the best use of rotating drum chambers in bioaerosol aging studies, this study aims to characterize the aerosol decay in a rotating drum, to determine the optimal rotation rate as a function of particle size, and to compare the theoretical predictions of Gruel's and Moss's models with experimental measurements.

METHODS

The experimental system comprises two compartments, the aerosol generation system and the rotatable drum unit as illustrated in Fig. 1. An ultrasonic atomizer (Model 8700-120MS, Sono-Tek Corporation, Poughkeepsie, NY, USA) is adopted to generate micrometer-sized PST (potassium sodium tartrate tetrahydrate, density 1.79 g/cm^3, $KOCO(CHOH)_2COONa\cdot 4H_2O$, A.C.S. grade, J.T.Baker®, Center Valley, PA, USA) particles as surrogates of bioaerosols. A syringe pump (KDS 200 / 200P, KD Scientific Inc., Holliston, MA, USA) is employed to deliver the solution to the ultrasonic atomizer to generate test particles. Then the particles are neutralized to the Boltzmann charge equilibrium using an aerosol neutralizer (10-mCi Am-241 radioactive source). The aerosol output is diluted with filtered, dried compressed air in an aerosol capacitance chamber which is 20 cm in diameter and 100 cm in height. Previous research (Ho, 2006) showed that the aerosol decay can be biased by aerosol coagulation when the initial aerosol concentration exceeds 10^5 particles/cm^3. To avoid measurement bias due to aerosol coagulation, the dilution air

is set at a flow rate of 60 L/min. An aerodynamic particle sizer (APS, Model 3321, TSI Inc., St. Paul, MN, USA) is employed to measure the aerosol number concentration and distribution in the aerodynamic size range of 0.5-20 μm. The APS can measure particle number concentration up to 1000 counts/cm^3 at diameters of 0.5 and 10 μm with coincidence errors less than 5% and 10%, respectively (TSI, 2012).

The acrylic rotating drum is 0.29 m in inner diameter and 0.59 m in length with a total volume of 39 L. The drum is mounted on a rack to allow free rotation on a horizontal axis and connected to an electric motor with a belt to attain the required rotation rate. Probes and sampling ports are installed on the non-rotating part of the drum. The temperature and relative humidity inside the chamber are monitored with a Temp/RH probe (HP 22, Rotronic Inc., Switzerland). A stainless tube, 0.34 m long by 4.2 mm inner diameter, is inserted into the drum with the inlet of the sampling probe positioned in the center of the rotating chamber. The outlet of the sampling probe is directly connected to the inner nozzle of the APS. Before each experiment, the chamber is purged with filtered compressed air until no aerosols are detected by the APS. The test aerosols are introduced into the rotating drum through the "A" valve and the excess air is vented through the "B" valve as illustrated in Fig. 1. Aerosols are introduced into the drum chamber for about 6 minutes to reach a stable particle concentration of approximately 170 particles/cm^3 during the drum experiments to prevent measurement bias due to coagulation effect. Then both "A" and "B" valves are closed and the air duct connecting the aerosol capacitance chamber and the rotating chamber is disconnected. The drum operates at the assigned rotating rate and the APS samples at 1 L/min. To balance for air loss to sampling, 2 L/min filtered compressed air is supplied into the drum through "C" valve and the excess air was vented. All the measurements are conducted in triplicate unless otherwise stated.

To examine the aerosol decay over time, the mean aerosol concentration after certain suspension period is divided by the initial aerosol concentration to obtain the suspended aerosol fraction. Goldberg (1958) assumed that the aerosol decay in a rotating drum could be expressed as a constant percent loss per unit time by the following equation.

$$N = N_0 exp^{-kt} \quad (6)$$

where N_0 is the initial aerosol number or concentration, N is the aerosol number or concentration after time t, and k is the aerosol decay constant. This first-order model for aerosol decay is governed by the particle aerodynamic properties and rotation rate of the drum.

RESULTS AND DISCUSSION

Bias versus sampling protocols

To evaluate the bias from dilution effect due to sampling, an experimental system is built as illustrated in the upper left box of Fig. 1. Ambient aerosols with a count median diameter (CMD) of 102 nm and a geometric standard deviation (GSD) of 1.98 are introduced into the rotating chamber to alleviate the effects of gravitational settling and centrifugal impaction. The total aerosol concentration is continuously monitored by a condensable particle counter (CPC, model 3022A, TSI Inc., St. Paul, MN, USA) at an inlet flow rate of 1 L/min under the drum rotation rates of 0, 5 and 20 rpm, respectively. Figure 2 shows the suspended aerosol fraction as a function of time during continuous sampling. No significant difference is found for the aerosol decay under different rotation rates. This is because the influence of gravity and rotation are both negligible for the sub-micrometer-sized aerosols being tested. As for aerosol dilution caused by sampling, the resulting decay constant is estimated to be 0.033 min^{-1}. It can be inferred that the total sampling time for completing the experiment is not allowed to exceed 93 seconds assuming a 5% tolerance of error. Otherwise, the dilution effect should be adjusted to obtain true decay constants.

According to the experimental setup shown in Fig. 1, it takes only 39 minutes to replace the air volume of the drum chamber under an ideal plug flow condition. Two sampling approaches including continuous sampling and intermittent sampling on the aerosol decay measurement are compared. The test aerosols with a CMD of 5.16 μm and a GSD of 1.67 are generated and introduced into the rotating chamber. Owing to the small radius of the drum used in this work, the drum is operated at a rotation rate of 5 rpm to retain more particles suspended than in a stationary drum chamber. For continuous sampling, the aerosol concentration in the rotating chamber is continuously monitored by the APS at 1 L/min throughout the 1-hr suspension period. As for intermittent sampling, the APS samples for 1 minute only at the beginning and at the end of the 1-hr suspension period with no air sampling in between. Approximately 5% air is withdrawn from the rotating chamber and the resulting bias on the aerosol decay measurement should be negligible. Figure 3 compares the suspended aerosol fraction versus particle size for both continuous and intermittent sampling after 1-hr suspension period. As is expected, larger particles decay faster than small particles due to gravitational settling. Moreover, the aerosol decay in the rotating chamber is significantly biased by continuous sampling and the calculated aerosol decay rates under continuous sampling are seven times more than those under intermittent sampling, especially for particles smaller than 5 μm. To avoid the bias from sampling protocol, the intermittent sampling approach with total sampling time not exceeding the abovementioned limitation (93 seconds) is adopted for the remaining experiments, unless otherwise specified.

Aerosol decay versus particle size

The aerosol concentrations in the rotating drum with a rotation rate of 5 rpm are measured by the APS for a sampling period of 15 seconds in every 15 minutes throughout the 1-hr suspension period. Figure 4 shows the aerosol decay over time for particle sizes of 1, 3, 5.1 and 7.2 μm. The straight lines demonstrate that the aerosol concentrations for each particle size in the

rotating chamber follow a first-order exponential decay. Moreover, larger particles decay faster than smaller particles as expected. The calculated decay constants for 1-, 3-, 5.1- and 7.2-μm particles are 0.0033 ± 0.0006, 0.0084 ± 0.0003, 0.016 ± 0.002, and 0.059 ± 0.005 min^{-1}, respectively. These results imply that the aerosol decay kinetics inside the rotating drum for different particle sizes can be estimated using the extrapolation method according to the decay constant calculated using short-term measurements of aerosol decay kinetics.

Aerosol decay as a function of time

To evaluate the aerosol decay over time inside a rotating drum, the test aerosols with a CMD of 5.16 μm and a GSD of 1.67 are generated and introduced into the drum which rotated at 5 rpm. The aerosol number concentrations as function of aerosol size, after rotating for 1, 4 and 24 hours are measured by the APS. Figure 5 shows the fraction of initial particles that remain suspended as functions of particle size and suspension time. The aerosols in the rotating chamber decay dramatically with increasing suspension time. For 1-μm particles, the suspended aerosol fractions are 92, 73 and 14% after 1, 4 and 24 hours of suspension, respectively. Moreover, aerosol decay tendency is more prominent for the beginning of the test as the particle size increases. For example, the suspended aerosol fraction for 2-μm particles varies from 80% for 1-hr suspension to 48% after 4-hr suspension as compared with the corresponding levels for 1-μm particles. The solid lines represent the results calculated using the extrapolation method according to the decay constants obtained from the aerosol decay kinetic measurements of half-hour suspension period. As can be observed, the calculated results match well with the measurements of 1, 4, and 24-hr suspension period. It is proved again that the aerosol concentration over an extended period of suspension time in a rotating chamber can be predicted using the decay constant measured within a limited time period.

240 Evidence shows that the retention of aerosols in rotating drums is less efficient than the
241 theoretical predicted data (Frostling, 1973; Sutton, 2005; Verreault et al., 2013; Verreault et al.,
242 2014). To comprehensively compare the experimental measurements with the existing
243 mathematical models, the fractions of suspended aerosols in the rotating drum as a function of
244 particle size are calculated for the suspension durations of 1, 4 and 24 hours using Eqs. (1) and
245 (3). Results of the calculations are also shown in Fig. 5 with the long-dash and dotted lines
246 representing the predictions of Gruel's model and Moss's model, respectively. Figure 6 shows the
247 ratio of experimental measurements and theoretical solutions using the two models. Both
248 mathematical models are found to significantly underestimate the aerosol decay in the rotating
249 drum. For 1-hr suspension time period, both Gruel's and Moss's models predict correctly the
250 suspended aerosol fraction for particles smaller than 5 μm. For those particles larger than 5 μm,
251 the differences between experimental and theoretical data may be partly attributed to
252 measurement bias because there are fewer particles of larger size after suspension duration. In
253 addition, as the challenged particles were injected into the drum chamber through the "A" valve,
254 this will affect the flow pattern inside the drum and the entering particles with some velocity
255 diffuse throughout the chamber volume will inevitably affect their path. The aerosol
256 concentration inside the chamber is initially not uniform. Eventually, the particles will become
257 fairly uniform throughout the chamber volume as stirred settling model is appropriate for
258 turbulent mixing due to the incoming particle flow and convective mixing due to small
259 temperature differences between air and chamber wall (Fuchs, 1964). On the other hand, it should
260 be noted that only gravitational and viscous drag forces are relevant and taken into consideration
261 in the mathematical models of Gruel and Moss (Gruel et al., 1987; Asgharian and Moss, 1992).
262 The aerosol motion along the horizontal axis is ignored. Forces due to electrostatic, diffusion,
263 pressure gradient and mutual collision are also not considered. In addition, as the drum is

assumed to be maintained in an isothermal condition, thermal gradient forces are excluded in the models. In a real situation, the gravitational gyration becomes the dominant transport mechanism as the drum starts to rotate. Sutton claimed that electrostatic forces due to triboelectric charging play an important role in determining the aerosol decay (Sutton, 2005). However, significant differences between our experimental data and Moss's mathematical model are still found after the effect of electrostatic forces was excluded by aerosol neutralization in this work. Convective diffusion is another possible mechanism proposed by Sutton (2005). However, no satisfactory explanation can be made due to the limitation of this experiment.

Aerosol decay as a function of rotation rate

The fractions of suspended particles are measured at the rotation rate varying from 0 to 20 rpm for 1-hr suspension time period. For better clarity, only the results of 0, 5 and 20 rpm are plotted in Fig. 7. As can be seen, the rotating drum chamber yields more suspended particles at 5 rpm than at stationary phase (0 rpm) and 20 rpm. For 2-μm particles, the fraction of suspended particles is 84% for 5 rpm but only 14 and 45% for the drum rotated at 0 and 20 rpm, respectively. The experimental results imply that the rotation of a drum chamber greatly enhances particle suspension and the rotating rate can be optimized to retain the suspended particles for an extended time period.

The theoretical model predictions of Gruel and Moss for different rotation rates are also shown in Fig. 7 as long-dashed and dotted lines, respectively. For the current drum geometry (drum radius = 14.5 cm), particles larger than 1.5 μm will deposit at the wall of a stationary drum (0 rpm) for 1-hr measurement time as estimated by Eq. (2) (also referred to as Moss's model). The mathematical model underestimated the fraction of suspended particles in a stationary drum. The underestimation may be due to convective or turbulent mixing caused by air compensation for sampling loss. When the drum starts to rotate, both models predict identical results on the

fraction of suspended particles at high rotation rate (20 rpm) and yield slight differences at low rotation rate (5 rpm) indicating the combined effect of gravitational settling and centrifugal deposition. In general, mathematical models tend to overestimate the fraction of suspended particles when the drum chamber is rotating and this is in good agreement with the findings of previous studies (Embury and Sutton, 2005; Sutton, 2005). Figure 8 shows the ratio of experimental measurements and numerical data at 0, 5 and 20 rpm, as a function of particle size. Both mathematical models predict accurately the suspended aerosol fraction for particles smaller than 5 μm at 5 rpm. However, particle residence is dramatically overestimated especially for larger particles at higher rotation rate. As abovementioned, the real case is likely very complicated whereas only gravitational and viscous drag forces were taken into consideration in the existing models.

Optimal rotation rate versus particle size

The particle size and rotation rate-dependent aerosol decay constants are plotted in Fig. 9. It is evident that there is a minimal decay constant for each particle size in the measured rotation rate range, implying that the drum rotation rate can be optimized to retain suspended particles for an extended time period during the experiments when the gravity force and centrifugal force are comparable in magnitude. An interesting trend of increase in optimal rotation rate with increasing particle size is observed. The optimal rotation rate as a function of particle size is shown in Fig. 10 and the optimal rotation rate (V in rpm) is found to be accurately predicted with particle size (d_p in μm) by the following equation.

$$V = 0.6007 d_p + 1.9159 \quad (7)$$

The optimal rotation rate varies from 2 to 7 rpm in the particle size range of 1 to 7 μm and is proportional to particle size. This finding is in agreement with Sutton's experimental results that the optimal rotation rate falls between 1 and 6 rpm (Sutton, 2005). As a rough estimate, it would

312 be a good guess to choose 5 rpm for prolonged residence time periods for the potential bioaerosol
313 size spectrum in aging studies based on our experimental findings. However, such predicted
314 result is inconsistent with the numerical studies of Gruel et al. (1987) and Asgharian and Moss
315 (1992). The optimal rotation rate is concluded to be independent of particle size for particles
316 smaller than 10 μm (Gruel et al., 1987) or 5 μm (Asgharian and Moss, 1992). Moreover, the
317 optimum rotation rates predicted by Moss's model for all particle sizes are quite similar and vary
318 from 0.29 to 1.41 rpm which is much lower than the experimental results obtained in this study
319 and the previous study (Embury and Sutton, 2005).

320 For practical application of a rotating drum chamber in bioaerosol aging experiments, it is
321 critical to retain the test microorganisms in aerosol phase throughout the experimental process.
322 Figure 11 shows aerosol residence time isopleths. Aerosol residence time is defined as the time
323 that 5% of initial suspended particles remain suspended and is calculated given the rotation rate
324 and aerosol decay constant are known. With the current drum geometry used in this work, the
325 optimal rotation rate between 2 and 4 rpm can suspend 1-μm particles for over 24 hours. The
326 operating range of drum rotation rate for large particles and long residence time is narrower than
327 that for small particles and short residence time, implying greater care required when adjusting
328 the optimal rate for large particles and long suspension duration.

329 **CONCLUSIONS AND RECOMMENDATIONS**

330 This study investigates the effects of various critical parameters on decay constants of
331 aerosols in the drum chamber. Experimental results are also compared with theoretical
332 predictions from two previous models of aerosol dynamics in a rotating drum. Since the
333 continuous sampling approach results in underestimation of the aerosol decay constants due to
334 the dilution effect, the following conclusions are drawn from the experimental results according
335 to the intermittent sampling protocol.

For micrometer-sized particles, a considerable delay of sedimentation can be achieved using the rotating drum. It is demonstrated that the aerosol concentration over an extended period of suspension time in a rotating chamber can be predicted using the decay constant, measured within a limited time period. With the current drum geometry, the optimal rotation rate varies from 2 to 7 rpm in the particle size range of 1 to 7 μm and is linearly proportional to particle size. When operating at the optimal rotation rate (2~4 rpm), 5% of 1-μm particles can remain suspended for over 24 hours. However, it is crucial to adjust the optimal rate carefully for large particles and long suspension duration. Although there are discrepancies between Moss's model and the experimental data and remain unresolved, the rotating drum chamber is still a useful tool and 5 rpm is recommended for bioaerosol aging studies.

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Figure Captions

Fig. 1. Schematic diagram of the experimental system.

Fig. 2. Decay kinetics of ambient aerosols by continuous sampling under rotation rates of 0, 5 and 20 rpm.

Fig. 3. Aerosol decay as a function of particle size for continuous and intermittent sampling for the duration of 1 hour at a rotation rate of 5 rpm.

Fig. 4. Aerosol decay as a function of time for particles of different sizes.

Fig. 5. Aerosol decay over time as a function of particle size at 5 rpm. Symbols represent experimental data and solid lines represent the suspended aerosol fraction calculated from the decay constant of a half-hour measurement period. Long-dash lines and dotted lines represent the results of Gruel et al. (1987) and Asgharian and Moss (1992), respectively.

Fig. 6. Ratios of the experimental data and numerical data predicted by Gruel et al. (1987) and Asgharian and Moss (1992) as a function of particle size at 5 rpm after 1, 4 and 24-hr suspension periods.

Fig. 7. Aerosol decay as a function of particle size. Symbols represent experimental data under different rotation conditions. Long-dash lines and dotted lines represent the results of Gruel et al (1987) and Asgharian and Moss (1992), respectively.

Fig. 8. Ratios of experimental data and numerical data respectively predicted by Gruel et al. (1987) and Asgharian and Moss (1992) as a function of particle size at 0, 5 and 20 rpm after 1-hr suspension period.

Fig. 9. Effect of rotation rate on aerosol decay constant as a function of particle size.

Fig. 10. Optimal rotation rates versus particle size.

Fig. 11. Aerosol retention time isopleths.

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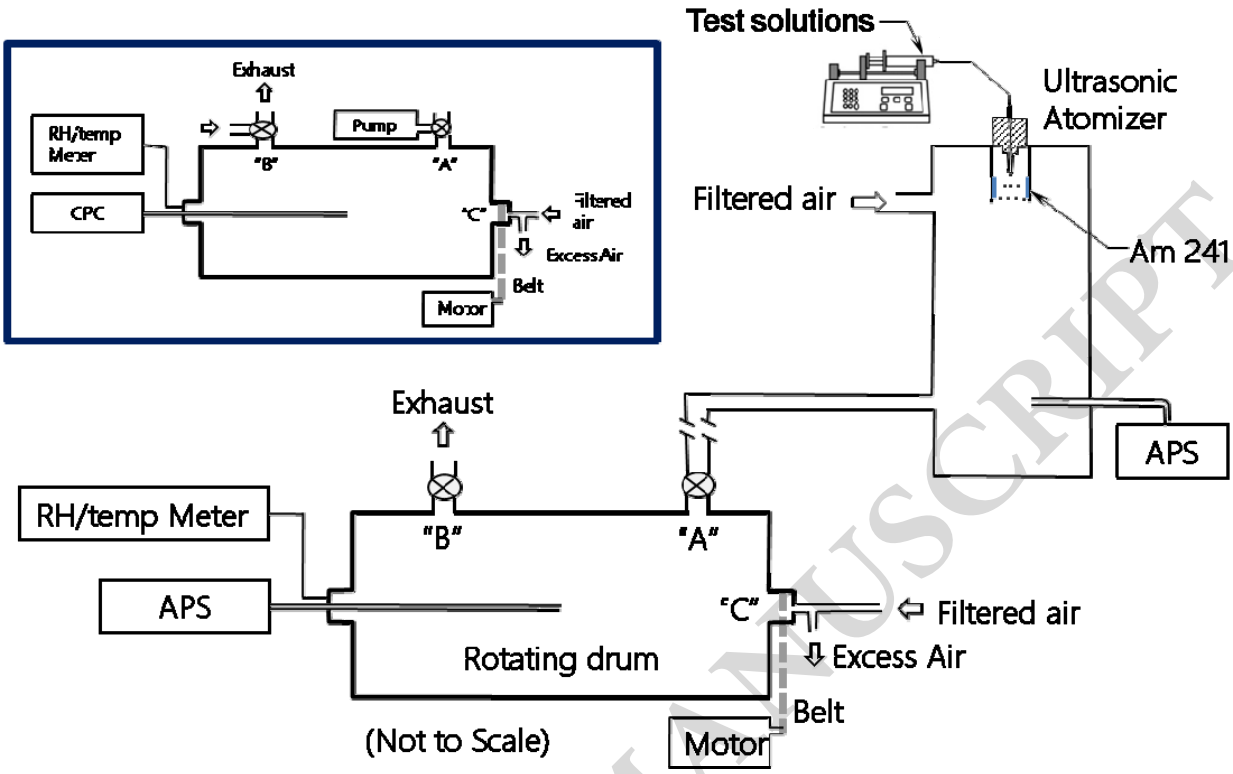

445

446 **Fig. 1.**

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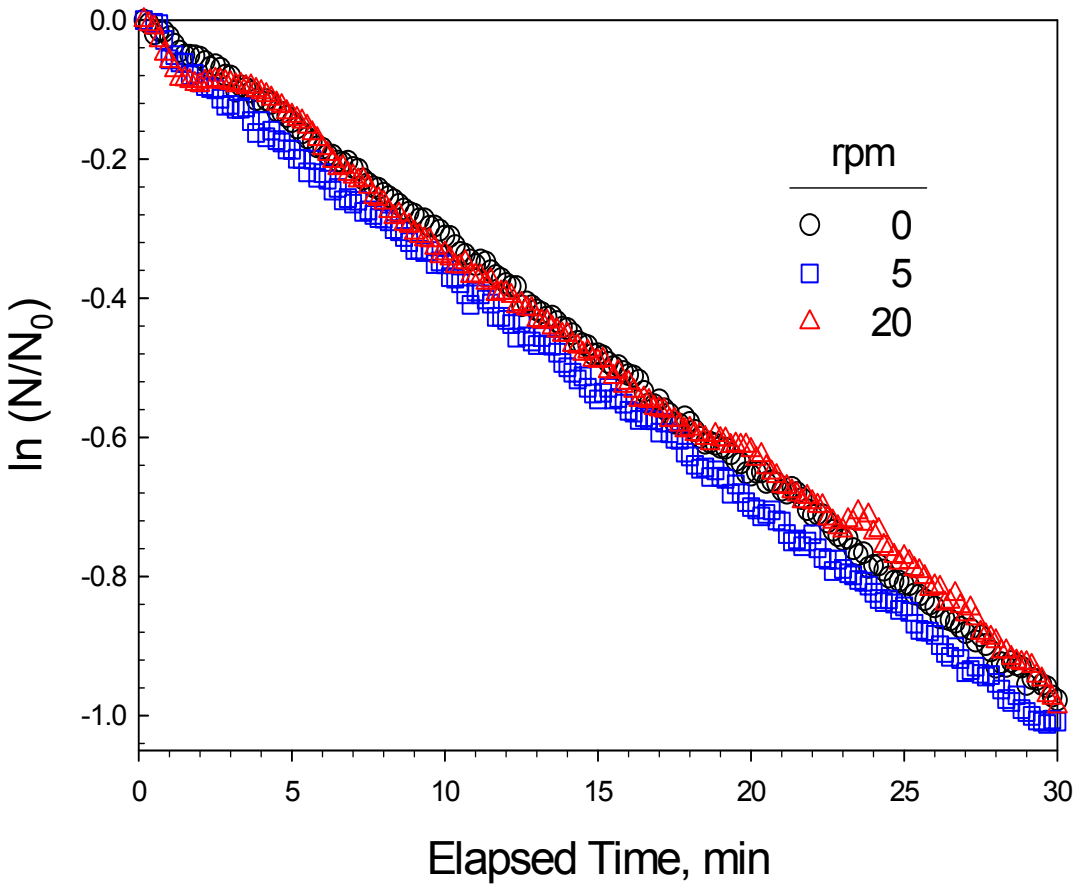

449

450 **Fig. 2.**

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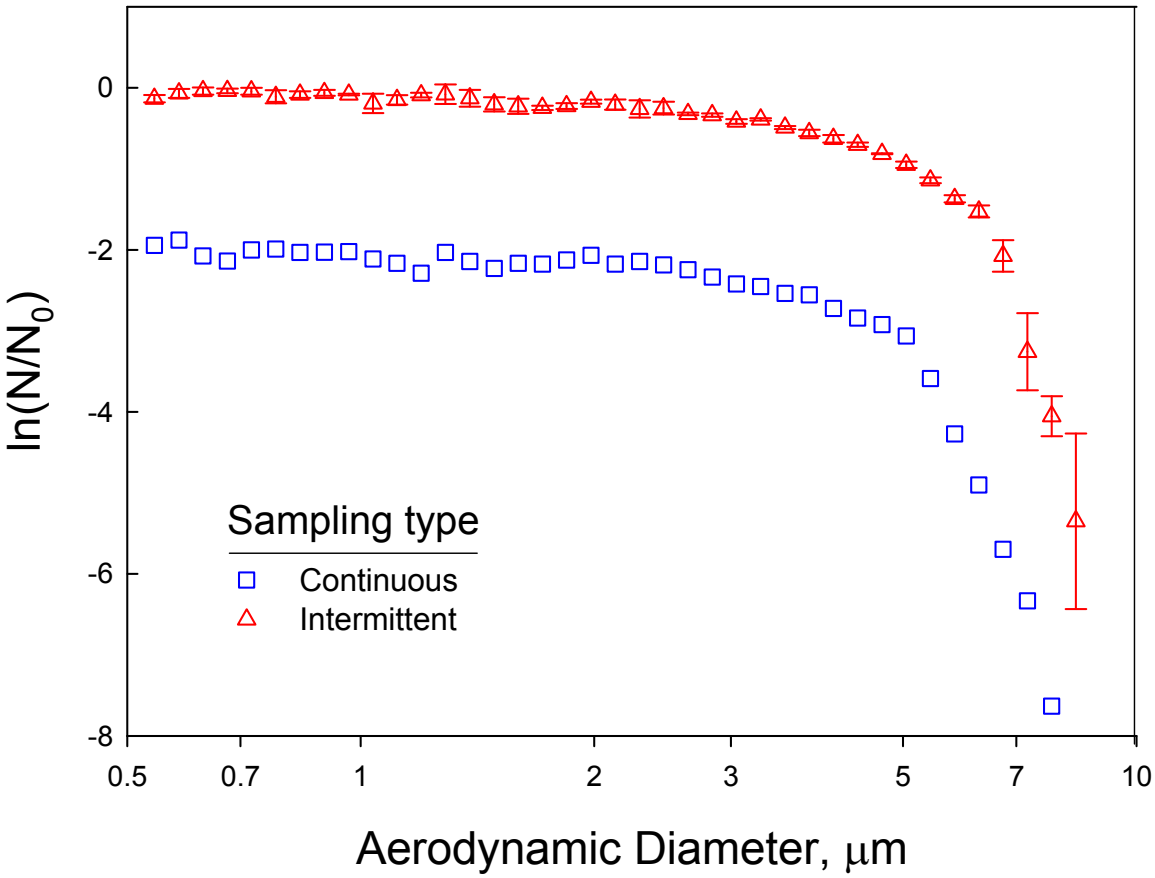

Fig. 3.

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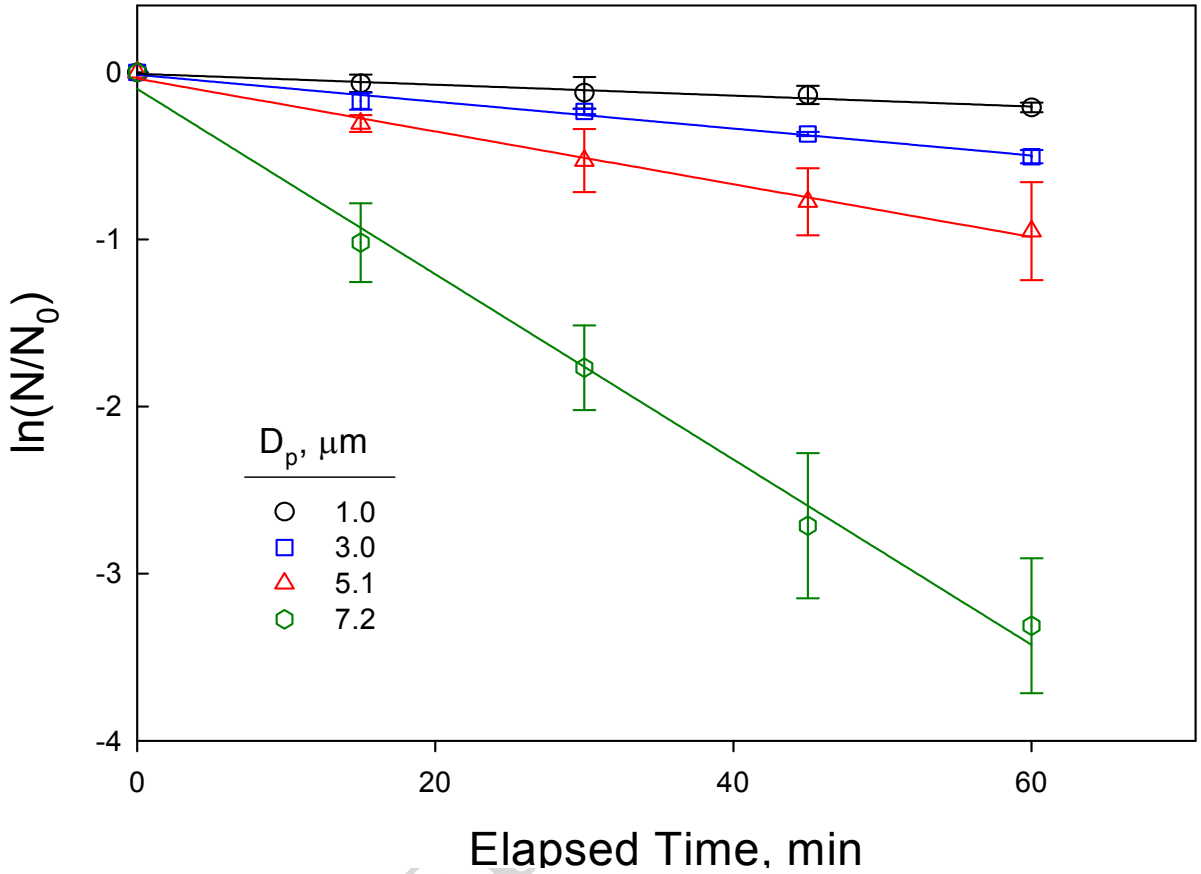

457

458 **Fig. 4.**

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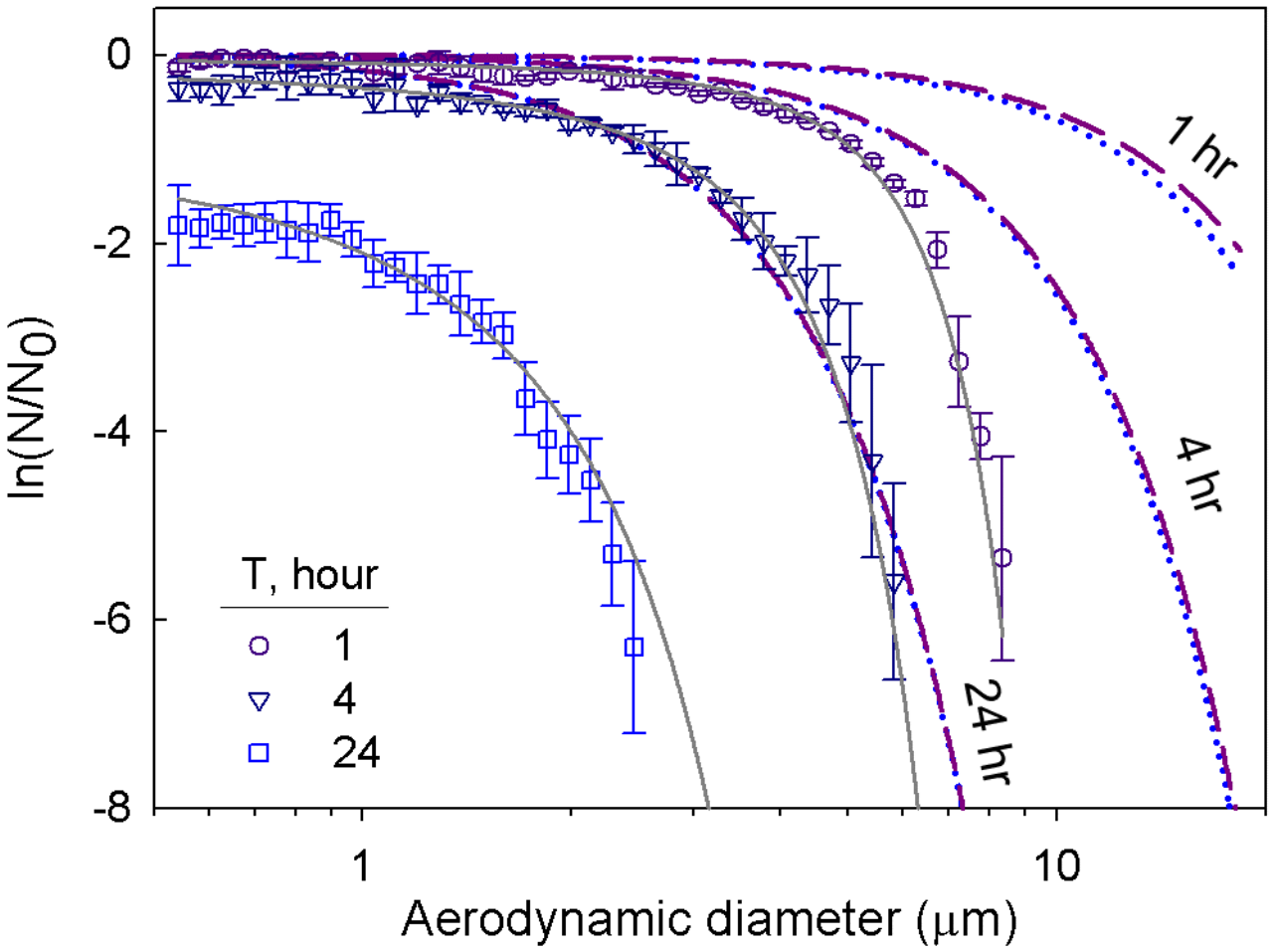

461

462 **Fig. 5.**

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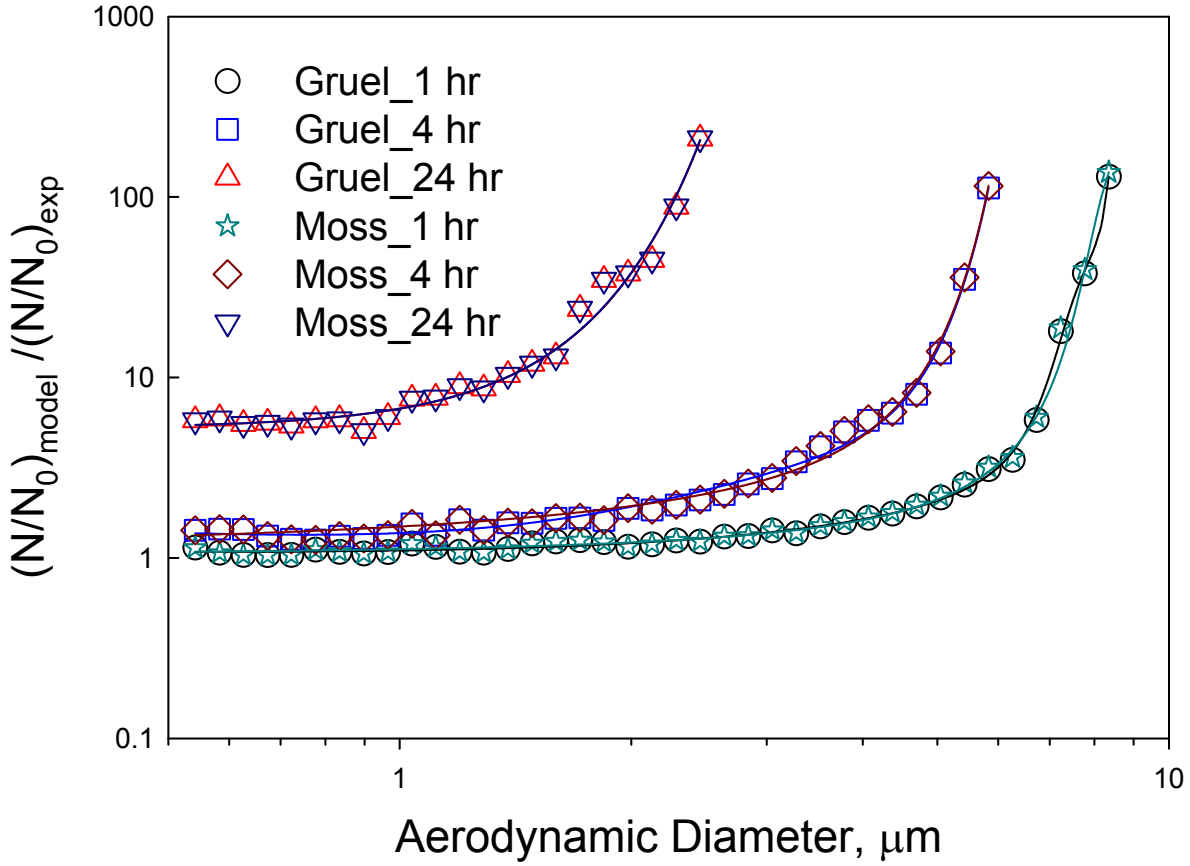

Fig. 6.

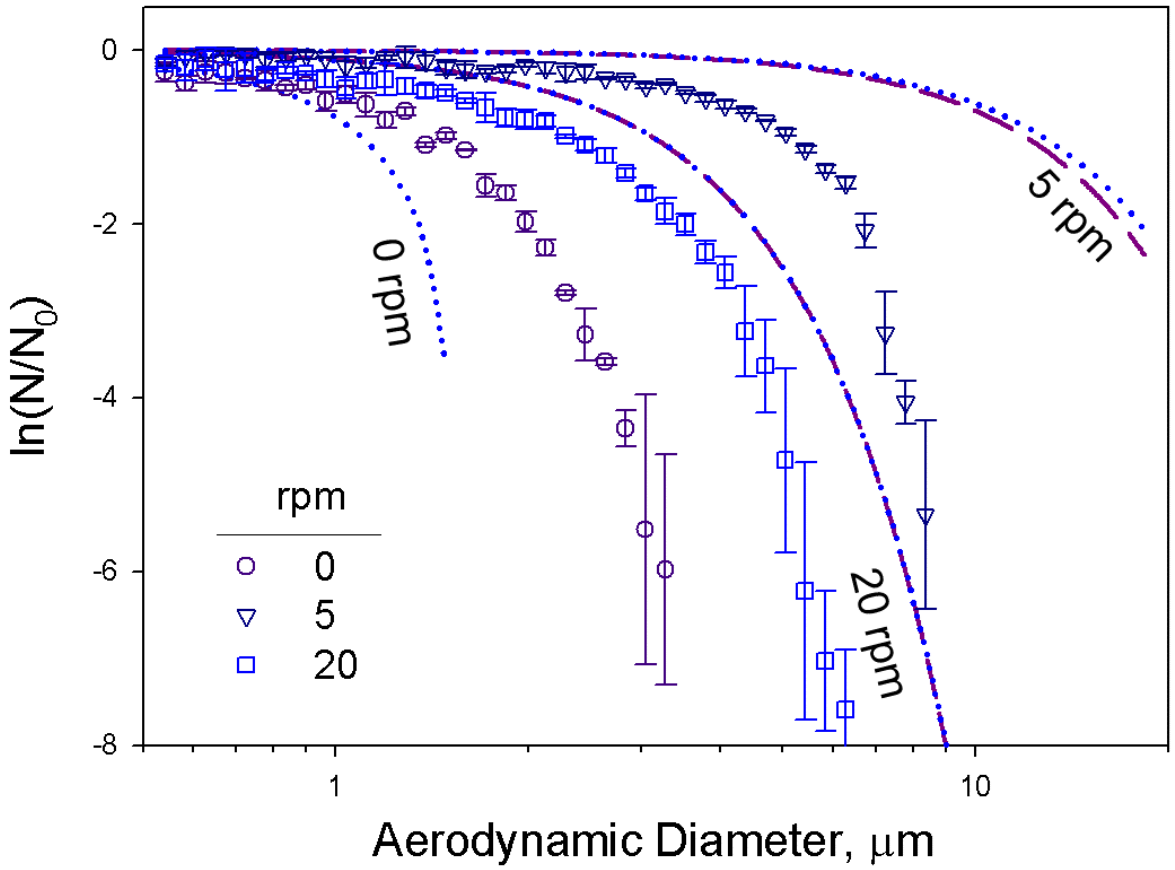

Fig. 7.

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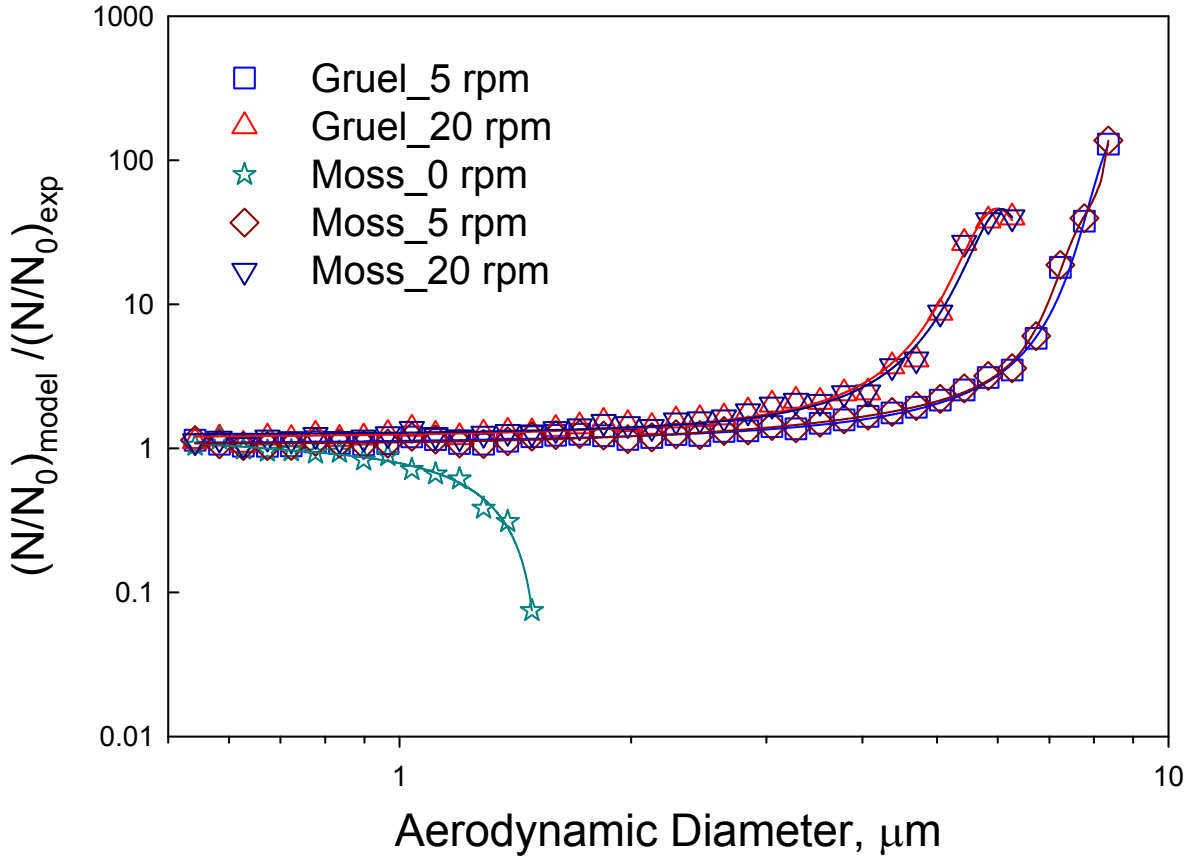

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474 **Fig. 8.**

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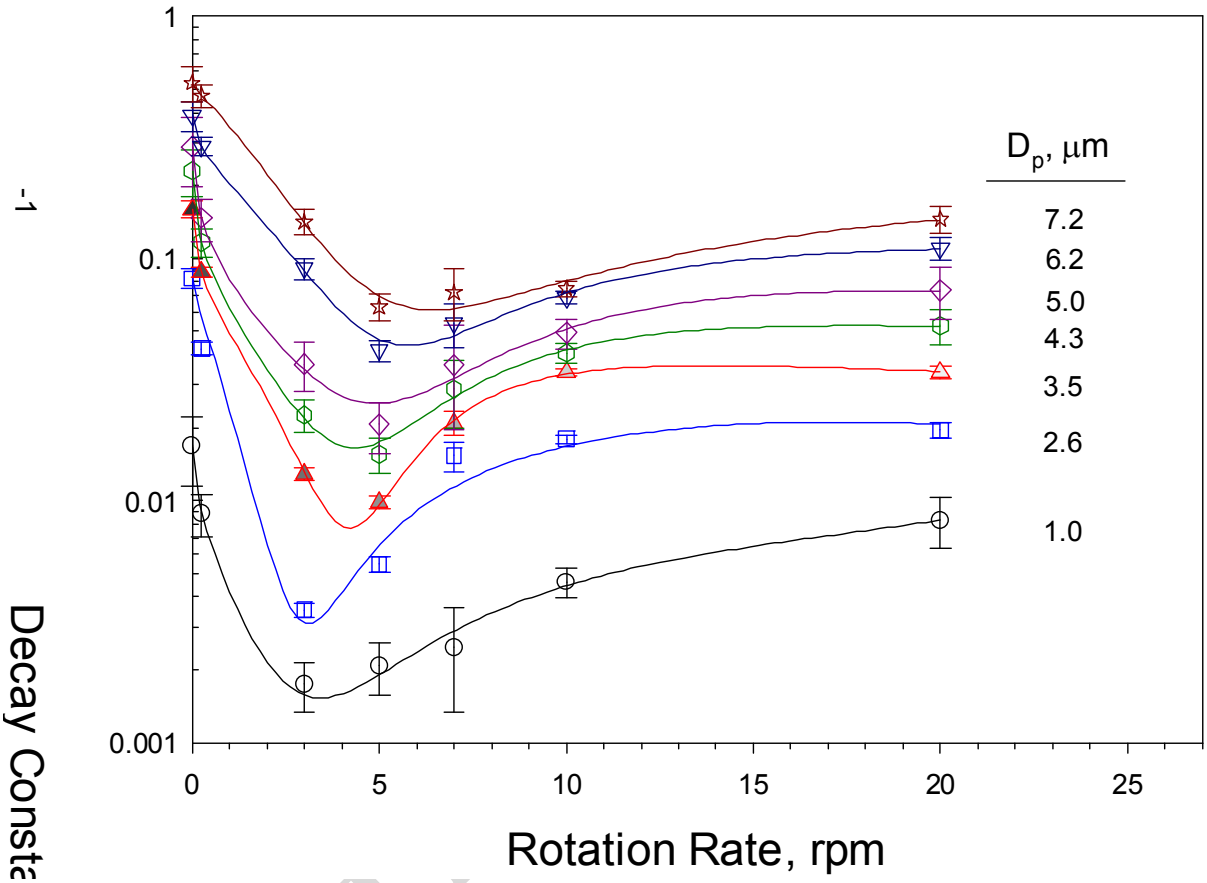

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479 **Fig. 9.**

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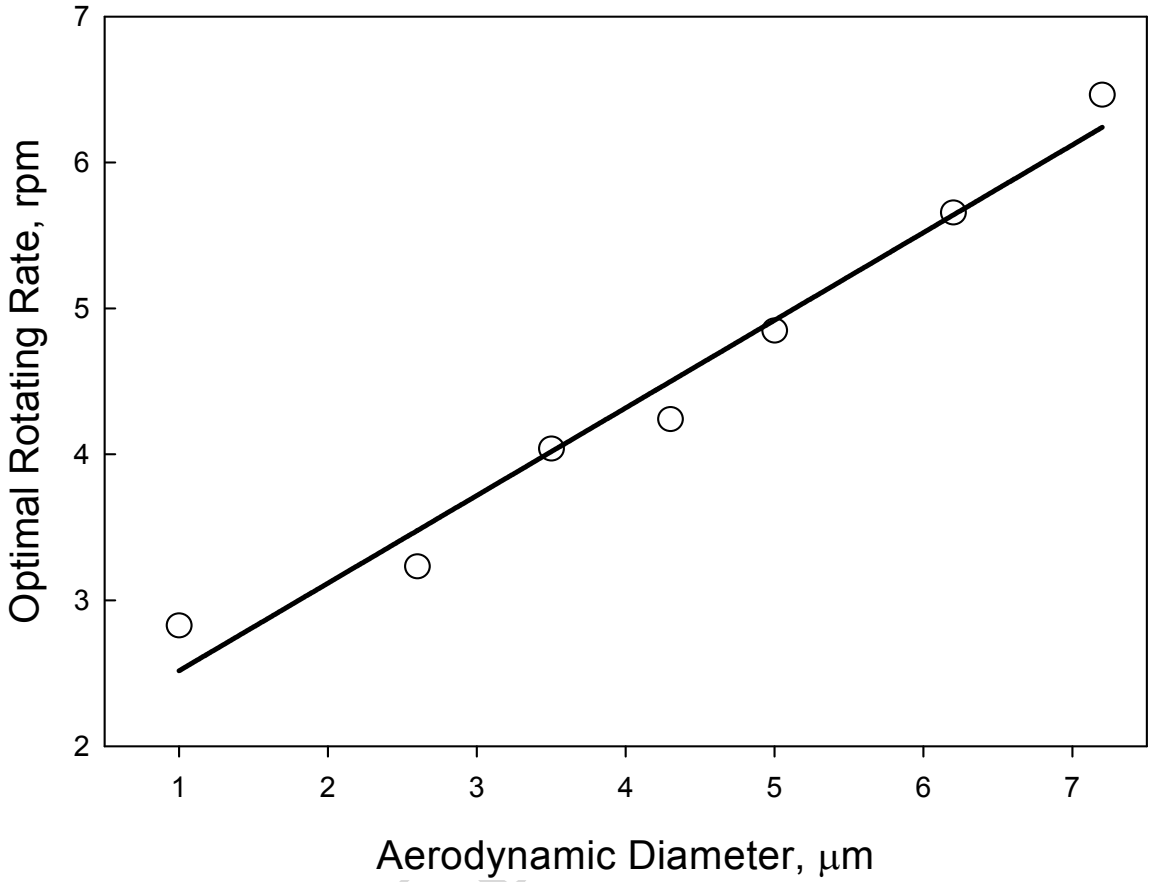

482

483 **Fig. 10.**

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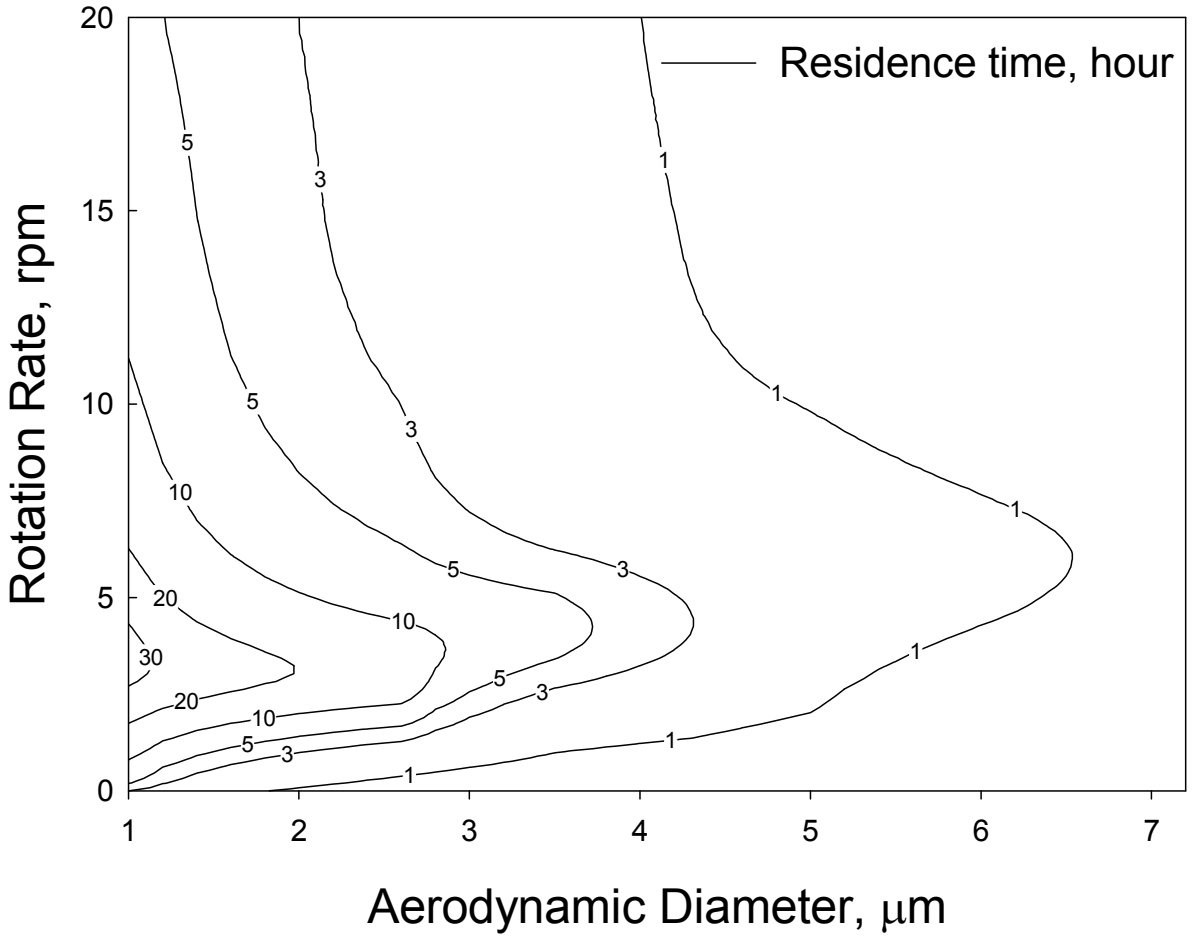

486

487 **Fig. 11.**

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