A Simple Method for Aerosol Transport Efficiency Tests in Sampling Tubes

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ABSTRACT

To obtain representative data, particle loss in sampling tubes must be minimal; otherwise, the magnitude of the losses must be known so it can be corrected. Since particle loss in sample tubes occurs through various mechanisms and depends on particle size, airflow velocity, and Reynolds number, there is no simple method to predict the particle loss of multitudinous configurations of sampling tubes. This study aims to present a simple method for experimentally determining particle loss as a function of particle sizes. Moreover, the applicability of existing models is verified experimentally.

An ultrasonic atomizing nozzle was used to generate micrometer-sized polydispersed particles as challenge aerosols. Following charge neutralization, the particle size distribution and number concentration upstream and downstream of the sampling tubes are measured by an Aerodynamic Particle Sizer. The particle loss in the sampling tubes with inner diameters of 4.5, 7.7, and 10 mm are measured at various values of Re (500–5000) and the tube orientations (horizontal and vertical). Both the horizontal and vertical tubes have the lowest loss at a Re of approximately 2100. Gravitational settling and turbulent-induced inertial impaction are the main deposition mechanisms in aerosol transport for particles larger than 1 µm. Gravity plays a significant role when the Re is less than 5000, then its dominant position is gradually replaced by turbulence with the Re continuing to increase. Further, the transport efficiency increased with increasing tube diameter. Consequently, each sampling tube needs to be tested according to the methods mentioned in this study to fully grasp the transport efficiency of particles through the sampling tube.

Keywords: Aerosol sampling, Method development, Particle transport efficiency, Sampling tube design, Reynolds number

1 INTRODUCTION

Improving the aerosol transport efficiency through tubes can increase the accuracy of measuring instruments (Marple and Chien, 1980; McMurry, 2000), reduce the risk assessment error of respiratory hazards in the workplace (Zhou and Cheng, 2005), and enhance the delivery efficiency during inhaled drug therapy (Ke et al., 2020). Especially in the field of environmental particulate matter (PM) monitoring, accurate monitoring data are the basis for formulating emission control strategies. Mastering particle transport efficiency can help people improve the design of measuring instruments and correct the results. However, transport efficiency tests for the instrument have not been widely carried out. Particle loss is still a significant problem affecting the representativeness of the monitoring data. This problem is particularly serious in the Particulate Matter Continuous Emission Monitoring System (PM CEMS).

A PM CEMS is a packaged equipment of sampling, analysis, and data processing devices deployed...
to provide critical information on flue gas. However, the accuracy and reliability of PM CEMS could be challenging because of the specific accuracy and performance requirements of the measuring sensors as well as the issue of continuously collecting representative aerosol samples containing a broad range of particle sizes. For an extractive PM CEMS, a sample tube is used to transport aerosol samples from the sampling inlet to the sensor. A study pointed out particles have a significant loss in the process of passing through the sampling tube from the stack to the particulate analyzer in the PM CEMS (Zhu et al., 2018). The loss leads to concentration underestimation and sampling bias. Besides, the loss fractions caused by different tube designs also differ. As a result, a simple and accurate method for particle loss quantified in sampling tubes is necessary.

The overall sampling efficiency of aerosol particles through sampling tubes is the product of aspiration efficiency and transport efficiency (Brockmann, 2011). The aspiration loss is caused by the velocity difference between the nozzle and flue gas and can be avoided by isokinetic sampling. The transport efficiency of particles through the sampling tubes has been developed for various mechanisms, including inertial impaction (Yeh, 1974; Crane and Evans, 1977; Diu and Yu, 1980), gravitational settling (Thomas, 1958), diffusion (Sinclair et al., 1976), and turbulence induced deposition (Schwendiman and Postma, 1962; Agarwal, 1975). In addition, thermophoresis can be important when sampling a hot aerosol stream through cooler tubing (Hinds, 1999). Further, losses can occur from electrical effects if the sampling tubes are made of non-conductors. In a word, particle deposition is a complex problem affected by many mechanisms (Chen and Yu, 1993).

Many efforts have been made to identify the transport efficiency of particles through sampling tubes treated experimentally. Fluorescent tracer techniques are the most common method for deposited particle quantification. Uranine (Liu and Agarwal, 1974; Pui et al., 1987; Chen and Pui, 1995; Gupta and McFarland, 2001) and Tritiated oleic acid (Ström, 1972) were used as the tracers and then collected by the filters or tubes for further washing operations and quantification. The experimental processes are so time-consuming and complicated that they cannot be carried out extensively. Besides, the sensitivity of radioactive substance solution, the quenching effect, and the extraction ability of the scrubbing solution may cause interference (Tseng, 1991). Therefore, the experimental data available in the literature are still limited. Advanced measurement techniques with high sensitivity and rapid time response have been developed in the past few years. However, there is no new method for rapidly confirming the transport efficiency with new techniques that has been widely used.

Table 1 displays many mathematical and semi-empirical formulas developed in the second half of the last century to predict the deposition fraction of aerosol particles in the sampling tube. When the laminar flow is in a horizontal tube, gravitational settling is the main mechanism causing particle deposition on the lower wall. Fuchs (1964) calculated the particle transport efficiency by assuming the particles settle in a parabolic trajectory. A gravitational deposition parameter $Z = (L/U) / (d/V_{ts})$ was introduced to determine whether a particle can pass through a tube. $L/U$ is the residence time of a particle in the tube, while $d/V_{ts}$ represents the particle settling time. $Z$ is the ratio of residence time to settling time. Schwendiman et al. (1975) developed a calculation model in the case of turbulent flow using the $Z$ parameter. Liu and Agarwal (1974) measured the particle deposition caused by turbulent flow in vertical tubes in the Re range of 10,000 to 50,000 and then developed a semi-empirical formula for prediction. Anand and McFarland (1989) combined Agarwal's (1975) turbulent diffusion model to create a new equation to predict the aerosol transport efficiency under the influence of gravity and turbulence in the sampling tube. They conducted experiments in the Re range of 1620 to 5050 to verify the model prediction accuracy. Although the total transport efficiency of a sampling tube for a given particle size can be calculated by multiplying the transmission efficiencies of all deposition mechanisms involved (Brockmann, 2011), it is only an approximation (Anand and McFarland, 1989). Besides, a sampling tube consists of a combination of straight tubes and elbows that could be laid in any orientation. Though the models might each have supportive experimental databases, they are for idealized airflow patterns and particle position distributions at the inlet. However, in practical application, the tube diameter converting, bending and environmental conditions will affect the inlet position of particles, resulting in deviation in prediction. A previous study showed the numerical predictions can meet only the cut-point (the particle with 50% transport efficiency), but not the slope of the experimental penetration curves (McFarland et al., 1991). This discrepancy might lead to a significant bias when aerosols are nearly monodispersed. Thus, there will always be a need for experimental validation in the laboratory or field.
Table 1. Calculation models of aerosol particle deposition.

| Model                          | Formula                                                                 | Nomenclature                                      | Operating range of Reynolds number |
|--------------------------------|-------------------------------------------------------------------------|---------------------------------------------------|-----------------------------------|
| **Fuchs, 1964**                | \[ \eta = 1 - \frac{2}{\pi} \left[ 2K \sqrt{1 - K^{\frac{1}{3}}} - K^{\frac{1}{3}} \frac{1}{\sqrt{1 - K^{\frac{1}{3}}}} \arcsin(K^{\frac{1}{3}}) \right] \] | \( \eta \): transport efficiency, \% \[ K = 0.75 \frac{2 \cos \theta}{\pi} \] | Laminar flow |
|                                | \( Z = \frac{L \nu}{D_U} \)                                            | \( Z \): gravitational deposition parameter      |                                    |
|                                | \( V_s = \frac{\rho_d D_i^2 g}{18 \mu} \)                              | \( V_s \): settling velocity, cm s\(^{-1}\)    |                                    |
|                                | \( V_s \sin \theta / U \ll 1 \)                                        | \( U \): wind velocity, cm s\(^{-1}\)           |                                    |
| Liu and Agarwal, 1974          | \[ \eta = \exp \left( -\frac{\pi Q V L}{D_i} \right) \]                | \( Q \): gas flow rate, cm\(^3\) s\(^{-1}\)    | \(10000–50000\) |
|                                | \( V = u_+ V \)                                                        | \( u_+ \): friction velocity, cm s\(^{-1}\)    |                                    |
|                                | \( V_s = (6 \times 10^{-4}) r_s^2 \)                                   | \( V_s \): particle deposition velocity, cm s\(^{-1}\) |                                    |
|                                | \( r_s = \frac{r_s^2}{u_+} \)                                         | \( r_s \): dimensionless particle deposition time |                                    |
|                                | \( \tau = \frac{\rho_d D_i^2}{C_c} \frac{18 \mu}{18 \mu} \)           | \( \tau \): dimensionless particle relaxation time |                                    |
|                                | \( C_c = 1 + \frac{1}{Re} \left[ 2.34 + 1.05 \exp(-0.39D_i/\lambda) \right] \) | \( \lambda \): mean free path, \(6.6 \times 10^{-6}\) cm |                                    |
|                                | \( u_+ = \frac{1}{2} \sqrt{f_2 U} \)                                   | \( f_2 \): friction factor                       |                                    |
|                                | \( f = 0.316/4Re^{0.25} \)                                             | \( Re \): Reynold number                         | \(> 2100\)                        |
|                                | \( \eta = \exp \left( -\frac{dL V_s}{Q} \right) \)                    | \( dL \): deposition velocity caused by turbulent diffusion, m s\(^{-1}\) |                                    |

With regard to PM sampling tubes, many studies have given suggestions. Thomas (1967) suggested the flow velocity in any sampling tube should be a higher Re in the air stream. Therefore, the sampling flow rate was recommended to be 150 times the tube diameter \((Re \sim 1200)\) to minimize the loss in the sampling tube. Ström (1972) found for a 16.8 mm inner diameter tube, the highest transport efficiency appeared when the Re equaled 2800. However, when the tube diameter differed from 16.8 mm, the Re corresponding to the maximum transport efficiency
varied for different size particles (Wong et al., 1996). Moreover, a prediction model discussing the combined effects of turbulence-induced deposition and gravitational settling of the particle also suggested the optimum tube diameter was not a constant Re (Anand and McFarland, 1989). Clearly, the optimal sampling flow rate cannot be generalized in a straightforward manner from past research results.

This study aimed to develop a simple method for rapidly quantifying the transport efficiency of aerosol particles in sampling tubes. Besides, the feasibility and convenience of this method were verified by experiments. Further, an optimization design principle for a straight sampling tube was proposed.

### 2 MATERIAL AND METHODS

Fig. 1 is a schematic diagram of the system used. The generation of micrometer-sized polydispersed particles was accomplished using an ultrasonic atomizing nozzle (Model 8700-120MS, Sono-Tek Corporation, Poughkeepsie, NY, USA) with a solution fed by a syringe pump (KDS 200P, KD Scientific Inc., Holliston, MA, USA). The ultrasonic atomizing nozzle converts high-frequency sound waves into mechanical energy acting upon the nozzle tip that creates standing waves in a liquid film. The volume median diameter of the solution droplets generated by the atomizing nozzle is about 18 µm. The dried particle size depends on the volume fraction of the residual materials in the solution. This study used di-ethyl-hexyl-sebacate (DEHS) and Sodium Chloride (NaCl) solutions as test agents to generate liquid and solid particles, respectively.

The generated droplets were passed through an aerosol charge neutralizer (radiation source, 25 mCi, Am-241) to neutralize their charge to Boltzmann equilibrium. The total aerosol charge in the test section of the experimental system was checked using an Aerosol Electrometer (model 3086A, TSI Inc., St. Paul, MN, USA). Besides, the tested sample tubes were properly grounded to earth with a ground electrode. The neutralized droplets were then mixed with 80 L min⁻¹ of filtered air to evaporate the solvent and obtain stable particle size distributions.

The aerosol number concentration and size distribution were measured using an aerodynamic particle sizer (APS, model 3321, TSI Inc., St. Paul, MN, USA). The APS covered particle sizes ranging from 0.5 to 20 µm and the aerosol number concentrations were up to 1000 count cm⁻³ with a coincidence error of less than 10% for 10 µm particles (TSI Inc., 2012). Since several researchers have shown the accelerating flow regime in the APS can cause liquid droplets to deform (Baron, 1986; Griffiths et al., 1986; Bartley et al., 2000; Baron et al., 2008) and subsequently cause errors in particle size measurement. This study, therefore, adjusted the size shifts of the DEHS particles measured by the APS using the air filtration technique. A polyurethane foam disc (diameter of 22.3 mm, thickness of 25 mm, PPI of 42) mounted on a specially designed holder was challenged with DEHS and NaCl particles, respectively. At a face velocity of 7.8 cm s⁻¹, the aerosol penetration curves of the foam disc were determined using DEHS and NaCl particles, respectively. Since the capture of micrometer-sized particles by the foam depends on the particle's aerodynamic...
Table 2. Experimental parameters of straight tube test.

| Parameters                              | Operating range         |
|-----------------------------------------|-------------------------|
| Inner diameter of sampling tube, mm     | 4.5, 7.7, 10            |
| Reynolds number                         | 500, 1500, 2100, 3000, 4000, 5000 |
| Size of challenge aerosols, µm          | 1–10                    |
| Length of tube, cm                      | 160                     |

Testing particles: NaCl, DEHS.

Dilution air: 80 L min⁻¹.

diameters, the true aerodynamic sizes of the DEHS droplets can be back-calculated according to the penetration of NaCl particles. Besides, polystyrene latex spheres (Duke Scientific Corporation, Palo Alto, CA, USA) were used to check the size accuracy of the APS. Moreover, the APS’s total and aerosol airflow rates were checked with a bubble meter before and after each test run (model Gilibrator-2 Calibrator, Sensidyne LP, St. Petersburg, FL, USA).

A 15 cm long sampling probe with the same diameter as that of the test tube was mounted on the chamber wall to eliminate the effects associated with aerosol aspiration and ensure full development of the flow field at its outlet. An external vacuum pump or a make-up air system was installed through a homemade adaptor to work with the APS to adjust the airflow rates in the testing tubes. The external flow rate was controlled using a mass flow controller (MFC, model MC-Series, Alicat Scientific Inc., Tucson, AZ, USA). The upstream aerosol samples were taken during the testing when the APS was connected directly to the sampling probe. Once a sample tube was connected, the downstream particle size distributions were measured. The transport efficiency of aerosol particles is the ratio of the downstream data to the upstream data. At least five replications were made for all the experiments. To avoid the effects of particle loading, the sample tube was cleaned after every five test runs.

As listed in Table 2, all the sample tubes used in the experiment were made of stainless steel, and their inner diameters were 4.5, 7.7, and 10 mm, respectively. The airflow rates through the sample tubes were set, resulting in Reynolds numbers (Re) in the range of 500–5000. Theoretically, a straight tube can be thought of as a combination of many identical short sections, each having a certain probability (γ) of collecting particles of a given size. Thus, the aerosol transport efficiency decreases exponentially with increasing tube length. Therefore, when γ is determined, the transport efficiency of a tube with any length can be calculated. In the present study, in order to have measurable deposition rates and at the same time consider the spatial limitation, the sample tubes of 160 cm in length were used. The experimental transport efficiency data were compared with the four models (Table 1) mentioned above to verify the applicability of the models.

3 RESULTS AND DISCUSSION

Before the transport efficiency tests, the APS size shifts for DEHS particles were conducted. The penetration data of the NaCl particles and DEHS droplets through the foam are shown in Fig. 2. The penetration of DEHS droplets is lower than that of NaCl particles due to the deformation of droplets in the measuring process of APS. Time-of-flight theory, which is employed in APS, uses accelerated flow to produce speed differences between aerosols with different aerodynamic diameters for further size determination. However, liquid particles are deformed into ellipsoids in the flow by the drag force, causing larger section areas as well as greater acceleration than spheres (Baron, 1986). Then, the deformed particles pass through the measuring unit in a shorter time. As a result, the aerodynamic size of liquid particles was underestimated. Therefore, a liquid particle size calibration process is needed before data analysis. In the present study, a calibration equation for liquid particle measuring in APS was developed using the penetration data in Fig. 2 and shown as follows:

\[ D_{true} = -0.0167D_{DEHS}^2 + 1.3845D_{DEHS} \] (1)

In the equation, \( D_{true} \) is the calibrated particle size, and the \( D_{DEHS} \) stands for the original measured size of liquid DEHS particles by APS.
The transport efficiency of the aerosol particles through tubes was tested and compared with previous models. Fig. 3 compares the experimental data and the Fuchs model in the horizontal tubes when the flow field is laminar (Re = 500, 1500, and 2100). The transport efficiency of the aerosol particles increased with increasing Re in both the model predictions and testing results. In horizontal tubes, gravitational settling was the primary mechanism causing deposition of micrometer-sized particle in laminar flow. Deposition of aerosol particles in cylindrical tubes by image force has been investigated theoretically and experimentally in several previous studies (Ljepojevic and Balachandran, 1993; Mayya and Sapra, 2002; Chang et al., 2012). It has been shown that the image force contributes significantly to a deposition only when the charge of the particle reaches an appreciable level which is much higher than that under Boltzmann charge equilibrium. For example, the deposition loss of 10 µm neutral particles flowing through a horizontal tube (I.D. = 4.5 mm, length = 160 cm, Re = 500) is about 68% calculated by Fuchs's model. In the meanwhile, the deposition loss of 10 µm charged particles (with 36 elementary charges) by image force is calculated to be about 0.067% using the method described in a previous study (Chang et al., 2012). Furthermore, since the fraction of particles carries 36 elementary charges (without regard to sign) at the Boltzmann equilibrium is less than 0.02%. Therefore, image force can be neglected in comparison with the other deposition mechanisms in the present study.

The results of turbulent flow are shown in Fig. 4. The data for Re = 3000, 4000, and 5000 were selected to compare the predicted results of the three turbulent models, respectively. Fig. 4(a) shows both the transport efficiency results of model prediction and experimental data increase with the increased Re. However, the predicted transport efficiency results are lower than the experimental data. Taking Re = 3000 as an example, the transport efficiency of 10 µm particles is overestimated by more than 60%. Since the model is a semi-empirical formula developed from the experimental data obtained under the Re range of 10000–50000 in a straight tube with an inner diameter of 1.27 cm. We used this model to verify the applicability of this model in the case of low Re turbulent flow and finally found it is not applicable in a range of Re less than 5000. As shown in Fig. 4(b), the changing trend of transport efficiency with wind velocity calculated by Schwendiman’s model was contrary to the experimental data. In Fig. 4(c), the trend of transport efficiency with wind velocity predicted by Anand and McFarland’s model and data was the same. In this case, the difference in transport efficiency in the particle size range of smaller than 5 µm
Fig. 3. A comparison between experimental data (Re from 500–2100) and a laminar model (Fuchs, 1964).

was less than 5% between the model and the data. At the same time, underestimation began to appear with continuous increases in particle size. This phenomenon agrees with the statement previously mentioned in the literature: for 10 µm particles, a significant prediction deviation appeared when the Re is about 5000 (Anand and McFarland, 1989). Besides, to analyze the difference between experimental and model data, the transport efficiency results of 3.3, 5.0, and 7.2 µm particles were selected to compare with the Fuchs and Anand and McFarland models in the Re range of 500–5000. As shown in Fig. 5, the experimental data are in good agreement with the Fuchs model in the laminar flow region. In the transition flow and turbulent region, the experimental data for 3.3 µm particles are consistent with the predicted model values. The model values for 5.0 and 7.2 µm particles are underestimated when the Re is higher than 4000. Moreover, Anand and McFarland’s model shows a good prediction performance in the laminar flow regime.

There is an optimal Re for sampling tubes with an inner diameter of less than 1 cm. Fig. 6 shows the aerosol transport efficiency data in the horizontal sampling tubes with inner diameters of 4.5, 7.7, and 10 mm in the Re range of 500–5000. The transport efficiency of particles has the same trend as the change in Re through different diameter tubes. The lowest particle loss appeared when the Re was 2100. Consequently, to obtain the highest transport efficiency, the Re of the tube flow should be set around 2100.

Aerosol transport tests in vertical tubes were carried out to analyze the separate contribution of gravitational settling and turbulent flow to particle deposition. As shown in Fig. 7, the tests were conducted in a 10 mm diameter tube. The particle transport efficiency gradually decreases with increasing Re, and approximately all particles can pass through the sampling tube in the laminar flow region (Re < 2100). When the wind velocity increases and the flow field gradually becomes the transition flow, the particles begin to deposit. The aerosol deposition rate increases with increasing turbulence intensity. Brownian diffusion has a negligible effect on particles larger than 1 µm (Brockmann et al., 1982; Darquenne, 2020). The sampling tube is grounded to eliminate the electrostatic effect during the experiment. Therefore, it is assumed the particle deposition mechanism in the horizontal tube is gravitational settling and turbulence. The dominating deposition mechanism in the vertical tube is turbulence. Hence, the difference in particle deposition between the horizontal and vertical tubes is the contribution of gravitational settling.
Fig. 4. A comparison between experimental data (Re from 3000–5000) and (a) Liu and Agarwal (1974), (b) Schwendiman et al. (1975), and (c) Anand and McFarland’s (1989) models. The solid lines represent the model predicting values, the hollow points are the experimental data, while the dots stand for the trend lines of the data.
Fig. 5. A comparison between the transport efficiency data of 3.3 µm, 5.0 µm, and 7.2 µm particles and the Anand and McFarland model in the Re range of 500–5000.

Fig. 8 shows the deposition loss caused by gravity and turbulence. With the increased wind velocity, the residence time of aerosol particles in the sampling tube decreases, and the contribution of gravitational settling decreases. In the Re range of 3000–5000, the testing range in the experiment belongs to the turbulent diffusion-eddy impact region (Guha, 1997) in terms of the dimensionless relaxation time mentioned by Anand and McFarland (1989). In this region, inertia plays an important role. Eddies in turbulent flow change the direction of particle motion, and the particles deviate from the streamline and collide with the walls due to their inertial, resulting in deposition loss. Therefore, the deposition rate increases with increasing particle size. Likewise, the higher the turbulence intensity, the greater the particle loss. For 10 µm particles, the loss caused by turbulence of the total loss under Re = 3000, 4000, and 5000, in this case, is 18.18%, 48.74%, and 76.41%, respectively. Fig. 9 compares the particle loss caused by gravitational settling and turbulence. The letter T represents turbulence-induced deposition and G is the gravity-induced particle loss. The figure shows when Re = 3000, the difference between deposition loss caused by turbulence and gravity (i.e., T-G) for particles larger than 1 µm is always negative, indicating gravitational settling is the dominant mechanism of particle loss under current conditions. When Re = 4000, the particle loss caused by turbulence gradually increases with increasing particle size, exceeding the gravitational settling effect, which becomes the dominant deposition mechanism. When Re ≥ 5000, turbulence is the predominant deposition mechanism for micrometer-sized neutral particles in straight tubes. The experimental results are consistent with the prediction of Li et al. (2018), showing gravity still plays an essential mechanism in the process of particle deposition in the low Returbulent flow (Re < 5000).

Tube diameter is also a key parameter to determine particle transport efficiency. In addition, in a practical situation, changing tube diameter is an easy way to control particle transport efficiency. The wind velocity, Reynolds number, particle residence time, and transport efficiency can all be adjusted by changing the tube diameter. Fig. 10 shows the transport efficiency of particles in both horizontal and vertical tubes with the different inner diameter at Re ≥ 3000. It can be seen that the Reynolds number was not the only parameter that guarantees the high aerosol transport efficiency in straight tubes. At a Reynolds number, although a straight tube with a larger inner diameter resulted in higher aerosol transport efficiency, a higher air flow rate should be applied.
4 CONCLUSIONS

The transport efficiency of 1–10 μm aerosol particles through horizontal and vertical tubes was tested to verify the feasibility of the testing method and to obtain the optimal design principles for the sampling tube to minimize particle loss. The results can be summarized as follows:
A simple experimental method was developed for evaluating the transport efficiency of 1–10 µm particles through sampling tubes in minutes.

2) The predicted transport efficiency values of the Fuchs model in the Re range of 500–2100 and the Anand and McFarland model in the Re range of 500–4000 could fit the experimental data well.

3) In horizontal tubes, particle loss could be minimized by setting the Re of the sampling flow at 2100. In vertical tubes, particle deposition began to occur when the Re was higher than 2100. Therefore, when sampling the PM, the Re of the sampling flow should be set at 2100 to achieve the highest transport efficiency. Meanwhile, the sampling time is now the shortest without particle deposition in vertical tubes.

4) In the Re range of 500–5000, the transport efficiency of aerosol particles was higher in the tubes with larger inner diameters. Therefore, the sampling tube with a larger diameter should be chosen.
Fig. 9. The contribution of turbulence and gravity on particle deposition.

Fig. 10. The comparison of aerosol transport efficiency in different diameter tubes versus different Reynolds numbers.
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