Development and Performance Evaluation of a Porous Tube Dilutor for Real-time Measurements of Fine Particles in High-humidity Environments (Secondary Publication)†

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Abstract

Real-time measurement of fine particles in stack emission gases is an important component of continuous environmental monitoring for PM_{10} and $PM_{2.5}$. We developed a porous tube dilutor (using both hot and cold dilution) to measure fine, but not condensable, particles in highly humid gas emissions, and compared our dilutor to a commercial ejector-type dilutor. Particle size distributions were measured in emissions from a diesel engine and a coal-fired boiler. The porous tube dilutor successfully measured particles in accumulation mode, including relatively large particles over 3 μm in diameter (without nuclei) whereas the ejector dilutor detected some condensable particles but could not detect large particles. The porous tube dilutor successfully removed condensed water droplets generated by a humidifier in a 30-m^3 chamber.

Keywords: Sampling; PM_{10}; $PM_{2.5}$; dilution; condensable

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INTRODUCTION

Health concerns arise on days with high PM_{10} or $PM_{2.5}$ levels (Health Effects Institute, 2017). To reduce PM_{10} or $PM_{2.5}$ levels, precise measurements at the source of PM_{10} and $PM_{2.5}$ are required so that the causes of generation can be analyzed and appropriate reduction technologies applied. Currently, fine particle measurements at fixed sources are performed manually via sampling and mass measuring; this takes at least 2–3 days and, potentially, over a week (Environmental Protection Agency, 1998). Thus, it is difficult to analyze fine particle emission status and control the concentrations thereof in real-time.

Most environments emitting fine particles are highly humid. When particles are measured using existing real-time instruments, it is impossible to precisely measure fine particles because of the presence of condensable particles generated during the sampling process (Lipsky et al., 2005). When measuring car emissions, a hot dilution method is used to suppress the generation of condensable particles (hot air is injected). Ejector and rotating disk dilutors using hot-dilution methods are commercially available (Lyyränen et al., 2004, Burtscher 2005, Li et al., 2011) (Figure 1). However, particle loss occurs during dilution, caused by air-mixing and cavity transport; it is difficult to precisely measure PM_{10} or $PM_{2.5}$ levels (Lipsky et al., 2002)

In this study, we developed a sampler with a porous tube dilutor (Deuerling et al., 2010) exhibiting low-level particle loss, and suppressed condensable particle generation. We compared our dilutor with a commercial ejector-type dilutor (DEED; Dekati Ltd., Kangasala, Finland) in

terms of measurement of particles emitted by a car diesel engine and a coal-fired boiler. Condensable particle suppression and the extent of large particle loss were compared. Condensable particle reduction characteristics were compared using a test chamber featuring high-level humidity.

METHODS

Figure 2 shows the porous tube dilutor. The first-dilution air (heated to 200°C) was introduced via a high-velocity ejector nozzle. The negative pressure created by the airflow allowed air containing fine particles to enter the sampling probe. The second-dilution air, at ambient temperature, was injected into the end of the ejector through a metallic, porous cylindrical tube filled with 20-μm-diameter beads. Particle loss at the inner wall during mixing at the end of the ejector was minimized by the porous structure.

First, to measure fine particles in diesel exhaust gas of high humidity and high temperature, a diesel engine was connected to a dynamo system. The displacement of the commercial car engine used (Santa Fé; Hyundai Motor Company, Seoul, Korea) was 1,991 mL, and the maximum output was 126 PS (92.7 kW) at 4,000 rpm. The engine oil employed was SAE 10W/30 (Hyundai Mobis, Seoul, Korea). Most experiments were performed at 2,000 rpm, with a torque of 18 kg·m and an exhaust gas temperature of 530°C. Using the DEED and our new diluting sampler, exhaust gas was sampled before passage through the diesel particulate filter (DPF) and analyzed

using the particle analyzer of the Scanning Mobility Particle Sizer (SMPS+C; Grimm Aerosol Technik Ainring GmbH & Co. KG, Ainring, Germany). The dilution ratios were fixed at 100 for the DEED and 10–20 for our new diluting sampler.

Fine particles were prepared using a 100,000 kcal/h coal-fired boiler (GV-10; Global Village Grand Vision Co., Ltd, Siheung-Si, Korea). The coal, Vietnamese anthracite, was supplied to the boiler at 20 kg/h. The temperature of hot water from the boiler was 70°C and that of the exhaust gas was 100–150°C during testing. The size distributions of fine particles from the coal boiler were measured (from 0.01 μm to 10 μm) using the SMPS+C device and an Optical Particle Counter (OPC) (model 1.109; Grimm Aerosol Technik Ainring GmbH & Co. KG, Ainring, Germany). We compared the DEED and our new dilutor.

When removing condensable particles from highly humid environments during dilution, changes in the levels of particles created by a humidifier (AOS-2055; Air-O-Swiss, Widnau, Switzerland) and an air purifier (FU-550; Sharp, Osaka, Japan) in a 30-m^3 test chamber (4.0 × 3.1 × 2.4 m) were measured using our dilutor. Test particles were prepared by atomizing KCl (1% w/v) solution using an atomizer (3076, TSI Inc., Shoreview, Minnesota, USA) combined with an aerosol neutralizer (3012, TSI Inc., Shoreview, Minnesota, USA) and diffusion drier; the humidifier was used to generate condensable particles. The air purifier was employed to control

KCl particle concentration. Changes in particle levels were measured by the OPC; the 0.25- and 0.35-μm channel particles were averaged to yield the levels of 0.3-μm particles per minute.

RESULTS AND DISCUSSION

Measurements of fine particles in diesel engine and coal-fired boiler exhausts

Figure 3 shows the particle size distributions of diesel engine exhaust flowing through our dilutor at different first-dilution airflow rates. The temperature of the first-dilution air was 200°C and the flow rate of ambient-dilution air (second-dilution) was 37 L/min. At 20 L/min of first-dilution air, peaks at 12 and 70 nm were evident. These were, respectively, the nuclei mode formed by saturation of condensable components (water or soluble organics), and the accumulation mode from particle accumulation. The particle numbers decreased slightly when the flow rates of first-dilution air increased from 20 to 22 and 24 L/min. However, the condensable nucleus decreased. When the first-dilution airflow rate exceeded 26 L/min, that nucleus disappeared but the particles associated with the 70-nm peak remained. The dilution air was of high temperature and low relative humidity. As the flow rate of the dilution air increased, condensable nucleation was suppressed; the particle numbers in the nucleus decreased. Thus, when sufficient hot air was supplied to the porous tube dilutor, particulate matter could be reliably measured in the absence of condensable particles.

Figure 4 shows the particle size distributions in diesel engine exhaust as measured by both the DEED and our new dilutor. The temperature of the first-dilution air for the DEED was 100°C. The nuclei mode particles were prominent when the dilution air temperature was too low. The size distribution of particles was similar to that of our porous tube dilutor, but the level was only 0.1-fold that of our new dilutor. Therefore, our dilutor suppressed condensable particle generation via a lower dilution airflow rate.

Figure 5 shows the particle size distributions in coal-fired boiler exhaust using the DEED and our new dilutor. The particle concentration was normalized to the total particle number to exclude the effect of different dilution ratios. The size distributions of accumulated particles were near-identical using the two kinds of dilutor. However, a condensable nucleus at about 0.01 μm was evident, and fine particles over 3 μm were absent, when the DEED was used. Thus, particles from 3–10 μm in diameter were not measured by the DEED, but were measured by our dilutor. Thus, our dilutor affords a low dilution ratio, no condensable particles, and minimal loss of large particles during mixing at the ejector.

Measurement of fine particles in the test chamber

Figure 6 shows changes in the levels of particles between 0.25 and 0.35 μm in diameter, as revealed by the OPC when KCl test particles were supplied to the test chamber by the atomizer when the humidifier was on. When the background concentration had attained a steady-state of

2–3 particles/cm^3 for 10 min, KCl particles were injected into the chamber over 10 min to 660 particles/cm^3, and the concentration was then held constant for the next 10 min. When the humidifier was switched on, the levels of 0.3-μm-diameter particles increased slowly for 12 min, and then rapidly. Finally, the concentration attained 1,170 particles/cm^3. In other words, the OPC could not distinguish water particles from test particles.

Figure 7 shows particle measurements in the 30-m^3 test chamber under various sampling conditions. The air purifier was operated in the low flow rate mode after injection of KCl particles. Sampling was performed with and without the dilutor, as dictated by the Korean air purifier test standard (SPS-KACA002-132). Then, dilutor sampling was performed once more during humidifier operation. The clean air delivery rate (CADR) of the air purifier can be calculated by multiplying 30 m^3 (the test chamber volume) by the decay constant k in the following equation: $C/C_0 = \exp(-kt)$. For the 'without dilutor' condition, the CADR was 2.43 m^3/min. For the 'with dilutor' and 'with dilutor during humidifier-on' conditions, the values ranged from 2.40 to 2.43 m^3/min. Thus, even if condensed water droplets are present, solid particles can be precisely measured by drying condensable particles in our new dilutor.

CONCLUSIONS

We developed a porous-tube dilutor featuring two-stage (hot and cold) dilution and found that this suppressed and removed condensable particles. Diesel engine exhaust particles exhibited a

bi-modal size distribution: a nuclei mode of condensable particles and an accumulation mode of solid particles. By increasing the flow rate of the first-dilution hot air into the porous tube dilutor, the condensable nucleus was suppressed, and the accumulated solid particles thus selectively measured. In terms of particles in coal-fired boiler exhaust, accumulated solid particles were also selectively measured. The loss rate of particles larger than 3 μm in diameter was lower than that of the ejector method (the DEED). Our new dilutor eliminated water particles by drying when water particles generated by a humidifier were mixed with solid particles, to be measured in a 30-m^3 test chamber; only the latter particles were separated and measured.

ACKNOWLEDGMENTS

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Figure Legends

Fig. 1. Commercial dilutors: (a) an ejector dilutor (Dekati® Dilutor), (b) a rotating disk dilutor (MD19-2E; Matter Engineering, Kirchberg, Switzerland).

Fig. 2. The porous tube dilutor used in this work.

Fig. 3. The size distributions of diesel particles at different first-dilution airflow rates at 200°C.

Fig. 4. The size distributions of diesel particles diluted by the ejector and porous tube dilutors.

Fig. 5. The size distributions of particles from a coal-fired boiler diluted using the ejector and porous tube dilutors.

Fig. 6. Changes in the levels of particles 0.25 to 0.35 μm in size after operation of the humidifier.

Fig. 7. Relative concentrations of 0.3-μm-diameter KCl particles over time after air cleaner operation under different dilution conditions.

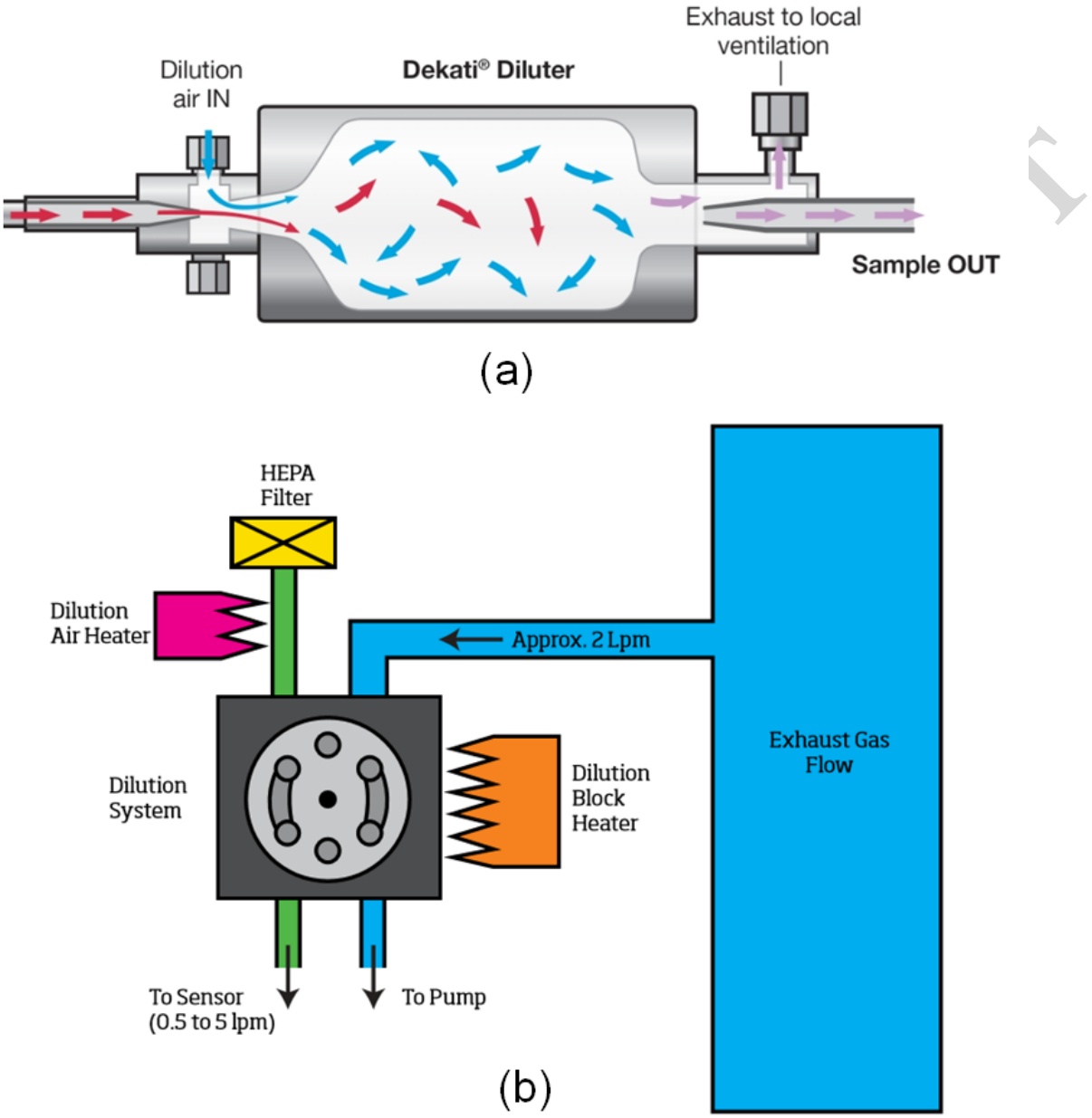
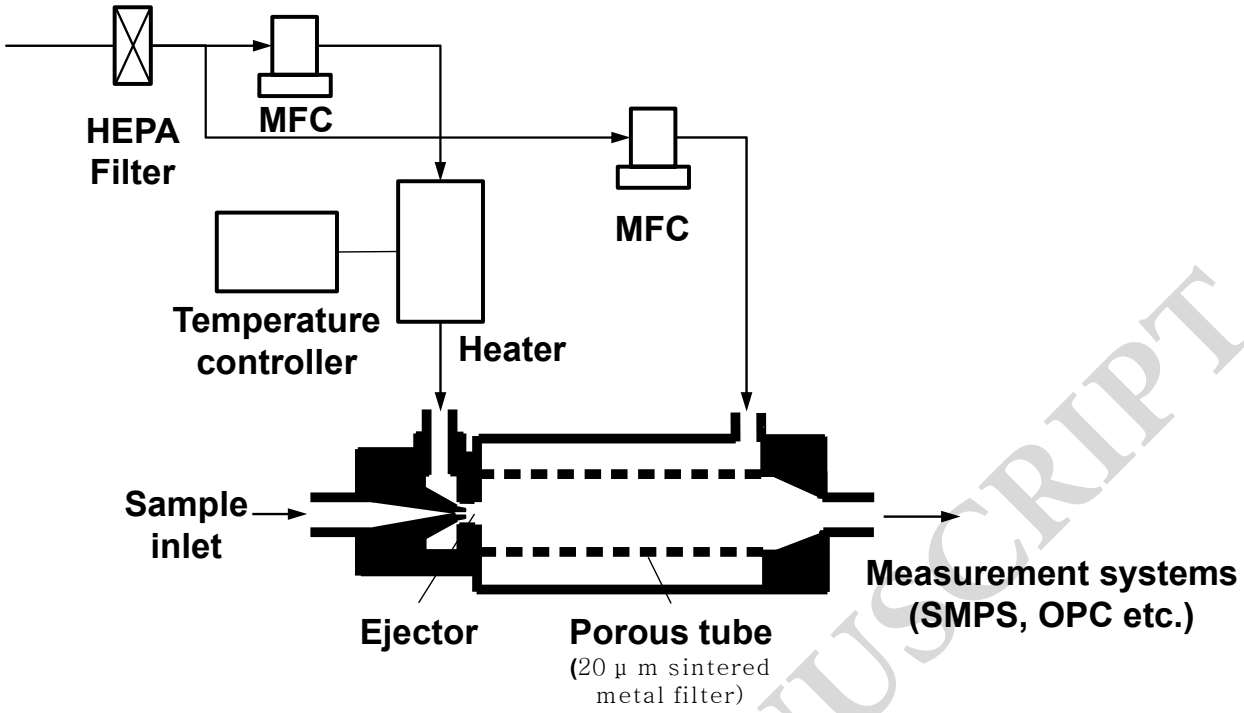

Exhaust to local ventilation
Dilution air IN
Dekati® Diluter
Sample OUT
(a)
HEPA Filter
Dilution Air Heater
Approx. 2 Lpm
Exhaust Gas Flow
Dilution System
Dilution Block Heater
To Sensor (0.5 to 5 lpm)
To Pump
(b)

Fig. 1.



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199 **Fig. 2.**

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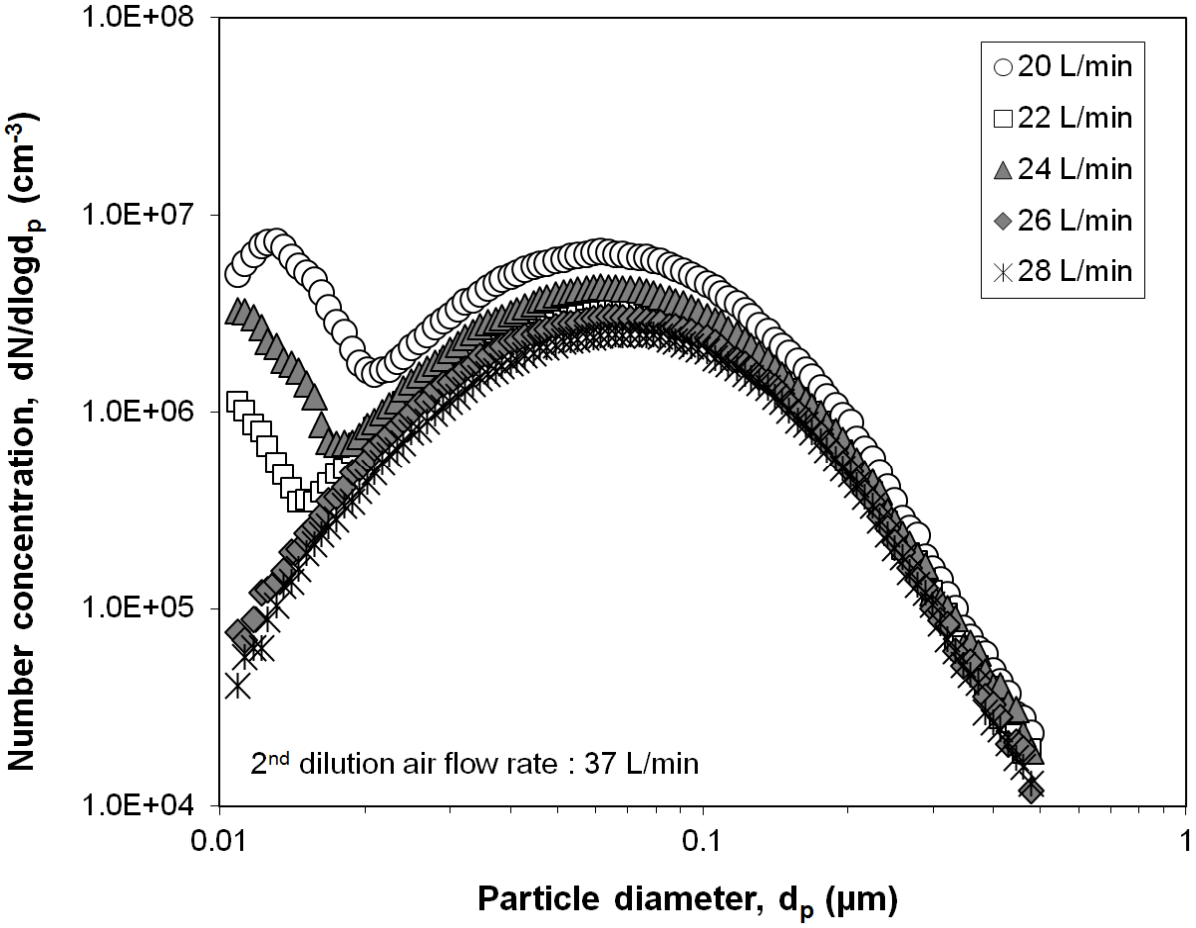

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203 **Fig. 3.**

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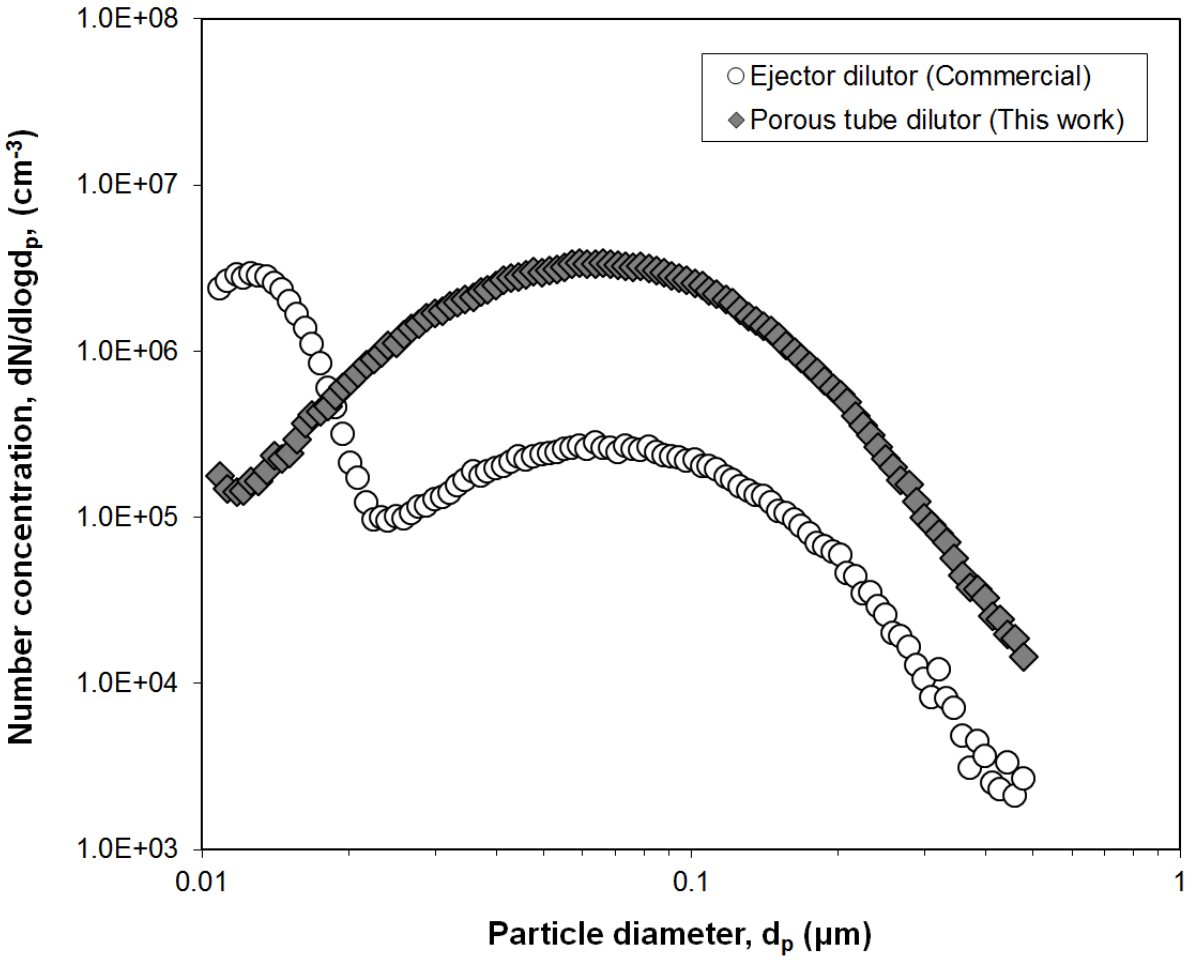

Fig. 4.

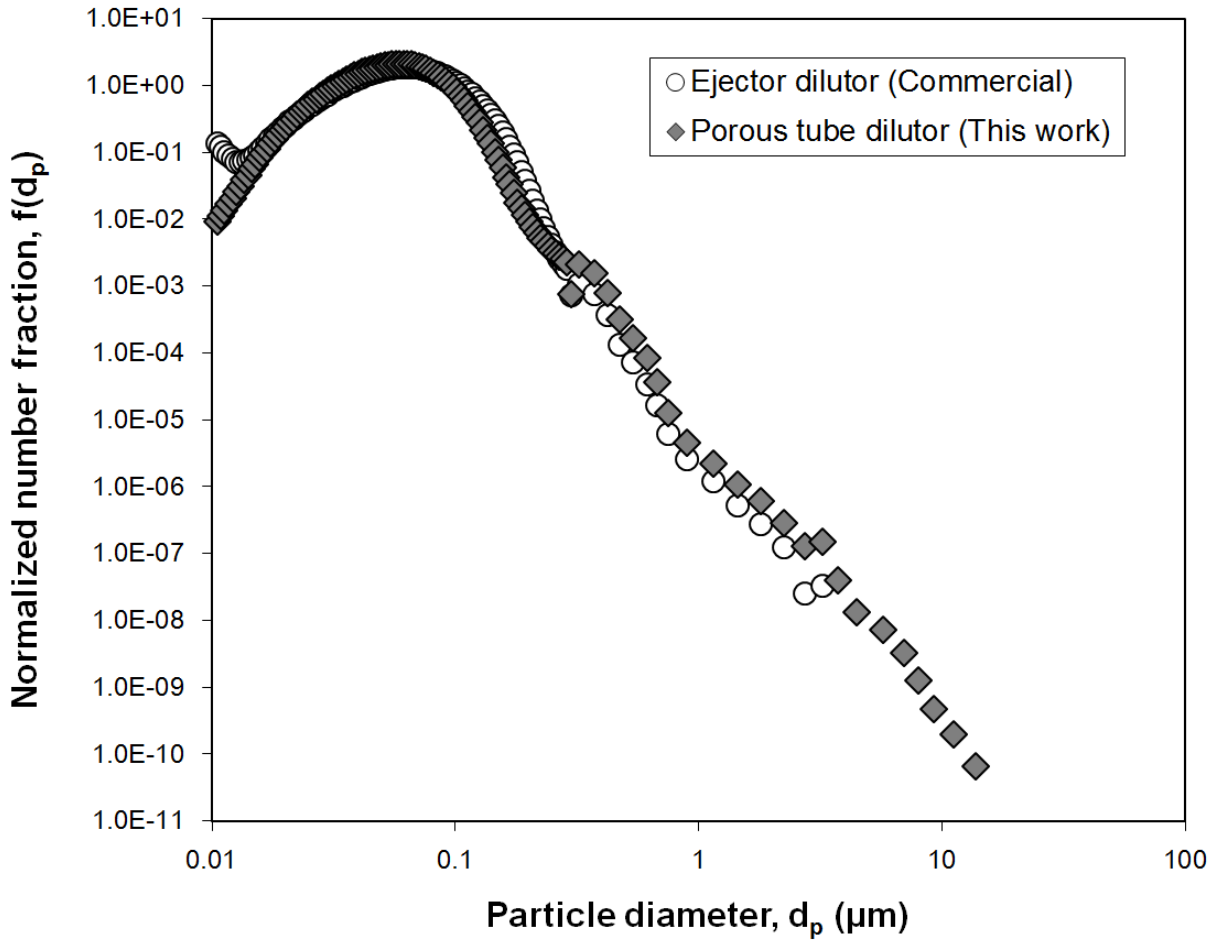

Fig. 5.

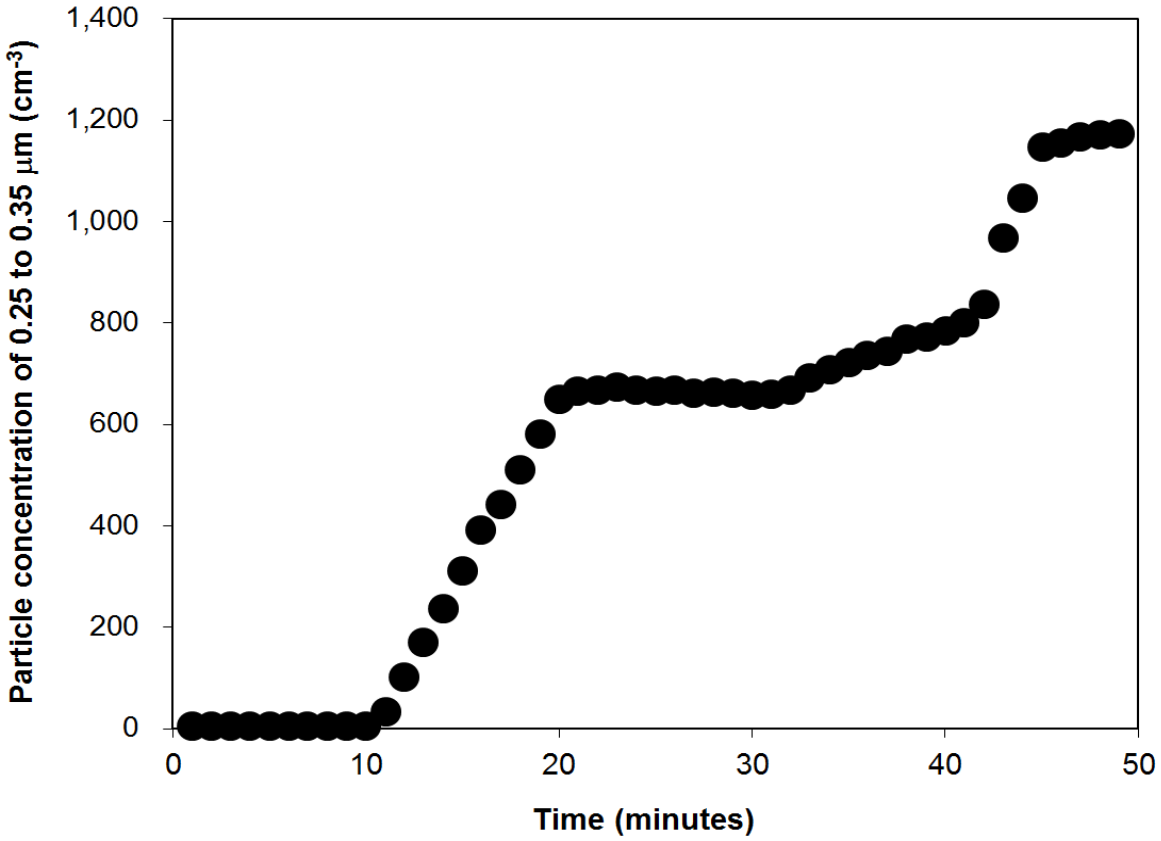

Fig. 6.

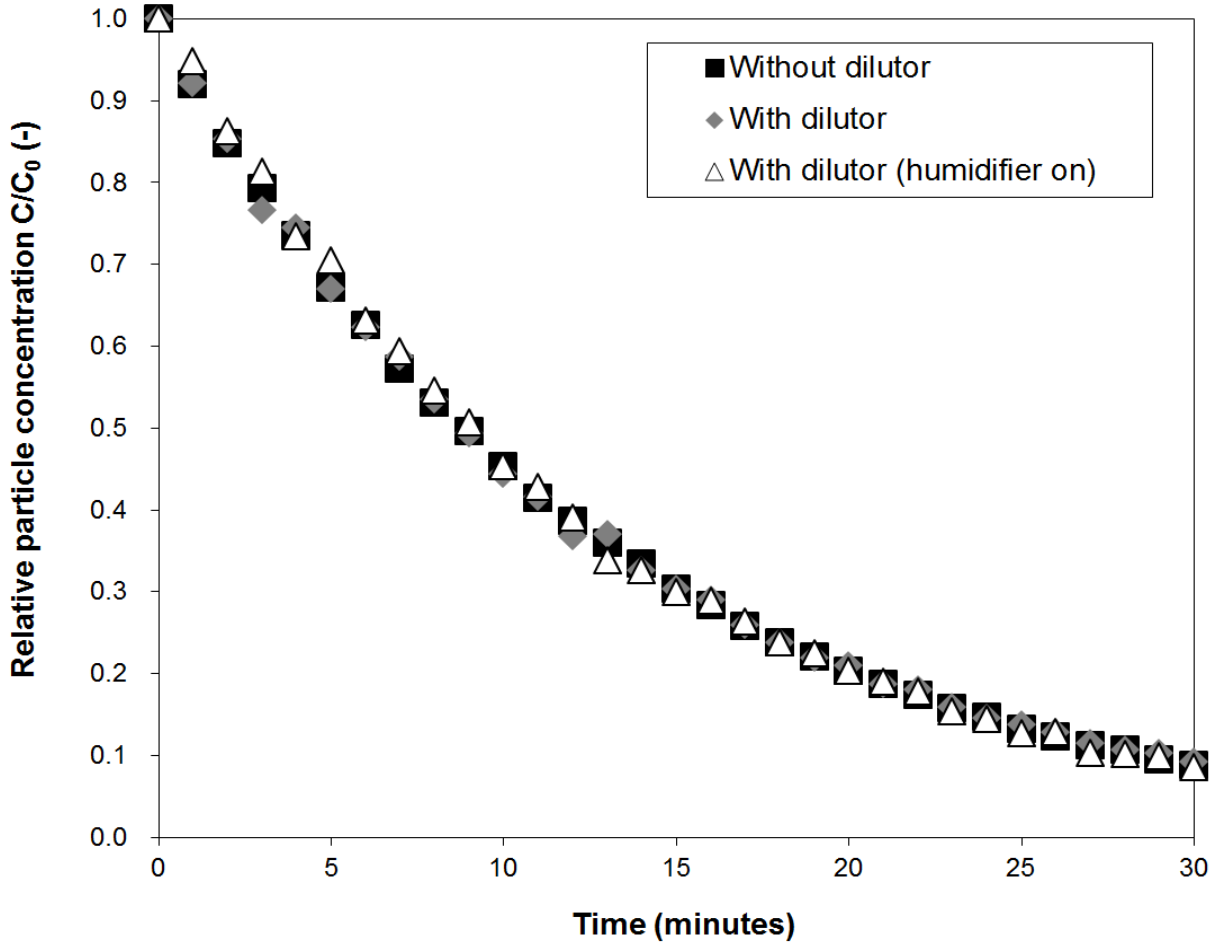
Without dilutor
With dilutor
With dilutor (humidifier on)
Relative particle concentration C/C0 (-)
Time (minutes)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30

Fig. 7.