

Diesel Exhaust Aerosol Measurements Using Air-Ejector and Porous Wall Dilution Techniques

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ABSTRACT

The objective of this work is to improve the understanding of variables like dilution and sampling conditions that contribute to particle-based emission measurements by assessing and comparing the nucleation tendency of Diesel aerosols when diluted with a porous wall dilutor or an air ejector in a laboratory setting. An air-ejector dilutor and typical dilution conditions were used to establish the baseline sensitivity to dilution conditions for the given engine operating condition. A porous tube dilutor was designed and special attention was given to integrating the dilutor with the exhaust pipe and residence time chamber. Results from this system were compared with the ejector dilutor. Exhaust aerosols were generated by a Deere 4045 Diesel engine running at low speed (1400 rpm) and low load (50 Nm, ~10% of rated). Primary dilution parameters that were varied included dilution air temperature (25 and 47°C) and dilution ratio (5, 14, and 55). Particle measurements were made at 0.3, 0.75, and 1.0 s to evaluate particle growth in the residence time chamber.

Exhaust size distribution measurements made using the ejector dilutor were bimodal with high concentrations of nucleation mode particles. Varying the dilution ratio from 5 to 55:1 (with a dilution air temperature of 25 °C and residence time of 1 s) led to the greatest change in the particle number concentration (4×10^8 to 4×10^{10} particles/cm³) compared to changes in the other variables. Particle concentration was lower with higher dilution air temperatures and particles were larger in size. Size distributions downstream of the porous tube and ejector dilutor were qualitatively similar in shape. Using a simple dilution model and equations for particle growth in the free molecular regime, particle growth in the two residence time chambers was compared. Model results suggest that dilution in the

porous tube dilution system occurs more slowly than in the ejector dilutor. This is consistent with the findings that the particle number concentrations were consistently higher and the geometric mean diameter was generally 1 to 5 nm larger downstream of the porous tube dilutor.

INTRODUCTION

Different sampling systems and methods are used to measure Diesel exhaust aerosol. The method is often optimized for a metric that is used to comply with a standard. Such is the case with the mass and number standards used to evaluate Diesel exhaust. However, a method optimized for one metric like mass is not necessarily optimized for particle number. Further, it is not uncommon for metrics to poorly correlate with each other (Mayer et al., 1998, Hall et al., 2001). Vouitsis, et al. (2003) reviewed many sampling methods, including those intended for measuring regulated and non-regulated emissions for low-emitting Diesel engines. Burtscher (2005) and Mohr (2005) reviewed many instruments and measurement principles with a focus on non-mass based measurements. Despite the many sampling methods and instruments available for measuring Diesel exhaust aerosol, no combination is totally satisfactory in all instances. This is particularly true for low mass emitting engines where particle number emissions are a concern, as is the case in the European Union. The University of Minnesota's engines laboratory has promoted the development of alternative methods to the gravimetric method for the measurement of Diesel exhaust aerosol (Swanson et al., 2010), and in this work designs for a porous tube dilutor and residence time chamber are presented.

In contrast to full-flow dilution tunnel measurements designed to determine compliance with a standard, laboratory measurements are often made in an attempt to mimic the particle size and concentration of Diesel aerosols found on-

road under real-world dilution conditions using partial flow systems. The Coordinating Research Council's E-43 project made particle number and size measurements on-road and tried to duplicate those measurements in the laboratory ([Kittelson et al., 2002, 2006a](#)). This study and others have shown that careful attention must be paid to mini-dilution tunnel (or residence time chamber) design and operation, dilutor geometry, dilution ratio, dilution rate, transfer line size and placement, residence time, heat loss, and dilution air temperature because these parameters influence nanoparticle formation. For these measurements, only a small fraction of the total exhaust flow is diluted often two or more times so that the resulting concentrations are within the range of the aerosol instrumentation. After primary dilution, the exhaust flows through a residence time chamber where particles nucleate and grow before being diluted again to further reduce the number concentration and to quench the aerosol growth process. Numerous studies ([Khalek et al. 1999, 2000, Kittelson et al., 2002](#)) have described in detail how many of these parameters impact nanoparticle formation. Their results show that nanoparticle formation is favored by low dilution air and dilution tunnel temperatures and high relative humidity. Particles appear larger as the residence time is increased due to growth via adsorption of gaseous compounds and coagulation. The dilution ratio and dilution rate are also important variables. The exact origin of the nucleation mode and the concentrations of precursor species are not often known so sensitivity analyses are needed to determine how strongly the dilution ratio and rate influence particle formation. Primary dilution ratios between 5 and 50:1 typically maximize particle formation. Typical secondary dilution ratios are also 5 to 50:1 but the exact value does not generally influence particle size or concentration. For a given engine condition, the dilution ratio that produces peak particle formation will depend on the sampling conditions and the concentration of gas phase species that contribute to nucleation and growth.

The literature reviewed above pertains to steady-state engine operation. Few researchers have attempted to evaluate semi-volatile particle size and number emissions during transient engine operation in the laboratory and those that do use typically must vary the dilution ratio ([Khalek et al., 2003, Ntziachristos et al., 2004, Liu et al., 2007](#)). In summary, because the formation of semi-volatile particles strongly depends on the sampling conditions, the variability of these methods is high. Even so, sampling systems and methods designed to mimic real-world dilution paying particular attention to quantifying solid and semi-volatile nanoparticles have been proposed ([Kasper, 2005](#)).

The focus of this work is to evaluate two parameters that impact the dilution process: dilutor geometry and the residence time chamber using two different dilution concepts: air-ejector and porous tube. Dilutor geometry determines how the exhaust sample is diluted, the rate at which it is diluted,

and it can impact particle losses. The residence time chamber is important because flowrates, temperatures, and pressures in this chamber depend on the primary dilution and influence particle growth and the particle size distribution. Therefore, the residence time chamber is specific to the dilutor geometry. Further design details are given in the experimental sections.

Both air-ejector and porous tube dilutors are widely used. In the porous tube dilutor, dilution air is introduced under slight pressure into a cylindrical stainless steel chamber through the walls of a porous sintered metal tube. The air permeates the porous tube, creating a virtual "wall" of air. As a result, particle and particle precursor losses are held to a minimum. The porous tube concept has been used previously in the literature with varying degrees of success. [Newton et al. \(1980\)](#) proposed an early version of porous tube dilution. [Mikkanen et al. \(2001\)](#) extended the concept to Diesel engine exhaust dilution. A commercial version (Dekati FPS) of Mikkanen et al.'s design is described in [Ntziachristos et al. \(2004\)](#). The European Particulates project evaluated a similar device and found that during steady-state and transient operation exhaust pulsations pulled and pushed exhaust in and out of the dilutor, causing a significant variation in dilution ratio. This consequence is less of an issue for the ejector dilutor because they operate at critical flow conditions. [Ntziachristos et al. \(2008\)](#) evaluated a concept where the exhaust gas was sampled at atmospheric pressure through capillary tube that was intended to reduce pulsations. They found that the new concept leads to constant DR sampling, independent of exhaust gas pressure and pressure variations. However, the very low flow through the capillary tube would lead to large losses in nanoparticle precursors. [Pyykönen et al. \(2007\)](#) modeled and experimentally measured nucleation in a perforated tube dilutor (similar but not the same as a porous tube) and concluded that a chemical component's "nucleation tendency" would be accurately reproduced in this type of dilutor.

In contrast to the porous tube, the air-ejector uses a venturi to draw a sample of exhaust before it is very turbulently and quickly mixed with dilution air. Air-ejector pumps have been used by [Khalek et al. \(1998, 1999\)](#), [Giechaskiel et al. \(2005\)](#), [Wong et al. \(2003\)](#), and [Kittelson et al. \(2002, 2005, 2006a\)](#). However, we found no studies that compared the impact of dilutor geometry on nanoparticle formation under constant sampling conditions. [Lyyrinen et al. \(2004\)](#) evaluated a porous tube dilutor, ejector dilutor, a AVL SPC 472 partial flow diluter, and various combinations of those listed but sampling conditions were also varied. Results suggested particle size and concentration depended strongly on dilutor geometry.

In this work, the alternative design of a porous tube dilutor is presented. The design is not given as an improvement over an existing design, but rather one that was optimized (size,

flowrates, pressure, etc) for use with a system that includes a transfer line, residence time chamber, and secondary dilutor. For comparison, a TD260 air-ejector manufactured by Air-Vac Engineering was evaluated. The design of a residence time chamber optimized to integrate with these dilution devices is presented and optimum design considerations are discussed. Exhaust aerosols were generated by a Deere 4045 Diesel engine running at low speed (1400 rpm) and low load (50 Nm). The primary dilution parameters varied included dilution air temperature and dilution ratio and particle measurements were made at various locations along the centerline to evaluate particle growth in the chamber.

EXPERIMENTAL SECTION

DILUTION SYSTEM DESIGN AND DESCRIPTION

Transfer Line

The transfer line is typically a short section of stainless tubing used to transport exhaust from the tailpipe or exhaust line directly to the dilutor. Wei et al. (2001a, b) showed that gas phase semi-volatile nanoparticle precursors can reversibly adsorb to the transfer line before primary dilution occurs, thus affecting the magnitude of the nucleation mode. To ensure a high transfer efficiency of particle precursors, exhaust must be transported using high flow rates and a relatively small value of the ratio of the transfer line surface area to the flowrate. Some dilution systems rely on a change in exhaust sample flow to change the dilution ratio. In such systems a change in the penetration of precursors will inevitably lead to a change in number concentration or size of particles that cannot solely be attributed to a change in the physics resulting from a change in dilution ratio. The solution is a system designed such that the penetration is near 100% for all cases.

The efficiency of transporting gas phase compounds in a tube is shown in Equation 1. For fully developed laminar flow, the penetration depends on the residence time (t), Sherwood number (Sh , 3.66), diffusion coefficient (D_i) and the diameter of the transfer line (D_t).

$$\text{Penetration} = \text{EXP} \left(-\frac{4 \cdot Sh \cdot D_i \cdot t}{D_t^2} \right) \quad (1)$$

This expression was used to calculate the penetration of tetracosane ($C_{24}H_{50}$) vapor for varying transfer line flowrates, lengths and temperatures where the transfer line inner diameter (ID) remained constant at 6.25 mm. The results are shown in Figure 1. The penetration of tetracosane vapor depends on the transfer line length, flowrate, and to a lesser extent, temperature. In the case shown, the penetration is >90% for typical exhaust temperatures and primary

dilution ratios commonly used. The transfer line length is a variable that is impacted by the type of dilutor and as shown in Figure 1 increases in line length reduce penetration. However, in this system, at a DR of 14 that corresponds to a total dilute exhaust flow 180 standard liters per minute (standard L/min), a centimeter change in the transfer line length results in a very small change in penetration (penetration is ~98%). As a result, the exhaust sample should be representative of the exhaust flow, penetration should not change between dilutors if the transfer line length is held constant, and the magnitude of the nucleation mode should be less sensitive to dilution parameters because the loss of semi-volatile material will be minimized. This calculation is semi-quantitative because we have assumed tetracosane is representative of the many HC species present in Diesel exhaust, and that there is no interaction of these HCs with each other or PM during the dilution process.

Transfer line lengths were nominally equal (10 cm) for the porous tube and ejector dilutor systems. In both cases the transfer line is held near the exhaust temperature via insulation. This is only practical due to the very short transfer line length, which is the recommended configuration. If longer lines are required, they should be heated to the exhaust temperature to minimize thermophoretic deposition.

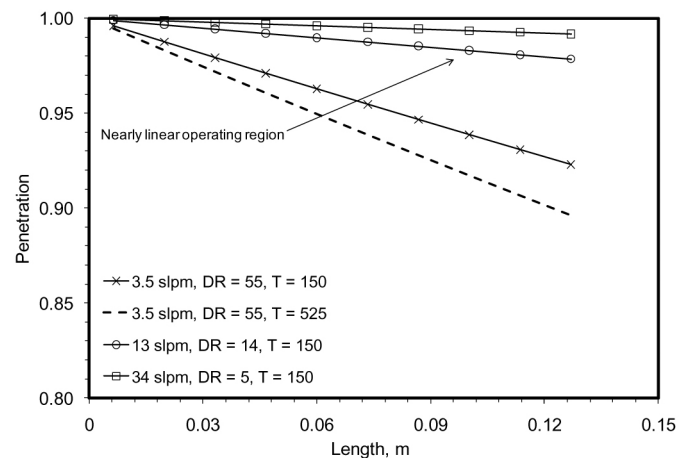


Figure 1. Penetration of gaseous nanoparticle precursors ($C_{24}H_{50}$) for varying transfer line flowrates (in standard L/min), lengths, and temperatures specific to our experiments conducted at 150 °C and one case shown for example for operation at 525°C. The transfer line inner diameter is 6.25 mm and the total dilute exhaust flow is 180 standard L/min. Temperature (T) is given in Celsius

Porous Tube Dilutor

The porous tube dilutor shown in Figure 2 consists of a porous stainless steel tube mounted concentrically within a stainless steel cylinder that is surrounded by a cooling jacket.