SCANNING MOBILITY PARTICLE SIZER™ (SMPS™) SPECTROMETER

BIBLIOGRAPHY

APPLICATION: COMBUSTION & EMISSIONS

2007

Chang, Yu-Chen; Lee, Hsiu-Wei; Tseng, Huan-Hsiung, 2007, "The formation of incense smoke," *Journal of Aerosol Science*, **38**(1):39–51

The formation of incense smoke generated from four different types of incense sticks, three manufactured in Taiwan and one in Japan, was investigated in a small controlled chamber. The scanning mobility particle sizer and the quartz crystal microbalance were used for particle size analyses. The count median diameter (CMD) was found to rise swiftly along the path of the incense smoke. Consequently, a representative sampling location was selected for all measurements performed thereafter. All four types of incense smoke were shown to exhibit characteristic size distributions, CMDs, and mass median aerodynamic diameters (MMADs). Electron microscopy depicted liquid and solid nature of Taiwan and Japan incense smoke, respectively. The different physical states of the particles were suspected to be a result of different smoke-generating ingredients used by different cultures. Finally, the formation mechanisms of both liquid and solid incense smoke were discussed.

Thierley, M; Grotheer, H.-H.; Aigner, M.; Yang, Z.; Abid, A.; Zhao, B.; Wang, H., 2007, "On existence of nanoparticles below the sooting threshold," *Proceedings of the Combustion Institute*, **31**(1):639–647

Nanometer-sized particles were studied by photoionisation mass spectrometry and scanning mobility particle sizer in laminar premixed ethylene flames above and below the critical sooting threshold. For sooting flames, both techniques detected a large number of particles with masses between 1 and 50 ku or diameter around a few nanometers. Neither method detected an appreciable number of particles below the sooting threshold in flames similar to those studied earlier for UV absorption and scattering of transparent soot. The absence of particle signals in both experimental techniques raises the question about the origin of UV absorption under nonsooting conditions.

Zhao, Bin; Uchikawa, Kei; Wang, Hai, 2007, "A comparative study of nanoparticles in premixed flames by scanning mobility particle sizer, small angle neutron scattering, and transmission electron microscopy," *Proceedings of the Combustion Institute*, **31**(1):851–860

Scanning mobility particle sizer (SMPS) and transmission electron microscopy (TEM) studies were conducted for TiO_2 and soot particles. The TiO_2 particles were produced from a premixed stagnation ethylene–oxygen–argon flame (ϕ = 0.36) doped with titanium tetraisopropoxide. Soot was generated from a burner-stabilized premixed ethylene–oxygen–argon flame (ϕ = 2.5). The close agreement among SMPS, TEM, and X-ray diffraction results for TiO_2 nanoparticles demonstrates that the probe sampling/mobility measurement technique is accurate for on-line analysis of the size distribution of particles as small as 3 nm in diameter. In the case of soot, notable disagreement between the SMPS and TEM sizes was found and attributable to the fact that the soot taken from the flame studied herein is liquid-like and that upon deposition on the TEM grid, the primary particles do not retain their sphericity. This interpretation is supported by measurements with photo ionization aerosol mass spectrometry, small angle neutron scattering, and thermocouple particle densitometry.

2006

Arai M.; Amagai K.; Nakaji T.; Hayashi S., 2006, "Primary and aggregate size distributions of PM in tail pipe emissions form diesel engines," *JSME International Journal, Series B: Fluids and Thermal Engineering*, **48**(4): 639–647

Particulate matter (PM) emission exhausted from diesel engine should be reduced to keep the clean air environment. PM emission was considered that it consisted of coarse and aggregate particles, and nuclei-mode particles of which diameter was less than 50nm. However the detail characteristics about these particles of the PM were still unknown and they were needed for more physically accurate measurement and more effective reduction of exhaust PM emission. In this study, the size distributions of solid particles in PM emission were reported. PMs in the tail-pipe emission were sampled from three type diesel engines. Sampled PM was chemically treated to separate the solid carbon fraction from other fractions such as soluble organic fraction (SOF). The electron microscopic and optical-manual size measurement procedures were used to determine the size distribution of primary particles those were formed through coagulation process from nuclei-mode particles and consisted in aggregate particles. The centrifugal sedimentation method was applied to measure the Stokes diameter of dry-soot. Aerodynamic diameters of nano and aggregate particles were measured with scanning mobility particle sizer (SMPS). The peak aggregate diameters detected by SMPS were fallen in the same size regime as the Stokes diameter of dry-soot. Both of primary and Stokes diameters of dry-soot decreased with increases of engine speed and excess air ratio. Also, the effects of fuel properties and engine types on primary and aggregate particle diameters were discussed.

Chan, Tat Leung; Dong, Gang, 2006, "Particle number and size distributions along the vehicular exhaust plume from a light-duty diesel vehicle," *Neiranji Xuebao/Transactions of CSICE (Chinese Society for Internal Combustion Engines)*, **24**(1):50–56

The characteristics of particle number and size distributions ranging from 15 nm to 30 µm along the vehicular exhaust plume emitted from a light-duty diesel vehicle under the low and high idling conditions were examined. The sampled exhaust particles were analyzed using the scanning mobility particle sizer (SMPS) and the aerodynamic particle sizer (APS) along the centerline of vehicular exhaust plume and under the environmental background. The results showed that the total particle number concentrations emitted from the tested diesel vehicle at high idling condition were much higher than those at low idling condition. However, the total particle number concentrations for both of idling conditions decreased with the distance departing from the exit port due to the deposition process. The results also indicated that most of particles from diesel vehicle were the fine particles less than 700 nm in diameter, and those particles would suspend longer time in the atmosphere than the large particles, resulting in the local particulate pollution. 16 Refs.

Cheung C.S.; Liu M.A.; Lee S.C.; Pan K.Y., "Experimental study on emission characteristics of diesel engines with diesel fuel blended with dimethyl carbonate," *Clean Air*, **6**(3): 239–253

In the present study, dimethyl carbonate (DMC) was blended with ultra-low sulphur diesel oil at different proportions, up to 30% by volume, and tested on a single cylinder direct-injection diesel engine, a 4-cylinder indirect-injection diesel engine, and a light-duty diesel vehicle to assess the effect of %DMC on fuel consumption and exhaust emissions. With an increase in %DMC, there was an increase in fuel consumption or a decrease in power output. Particulate emissions were measured with a scanning mobility particle sizer and an aerodynamic particle sizer. DMC was found to significantly reduce particulate emissions, both sub-micron and micron, but the reduction was not proportional to the %DMC in the blended fuel. Within addition to the reduction in particulate emissions, there was a slight decrease in NOx and a slight increase in CO. For HC, there was a reduction at 5%DMC but an increase at higher %DMC. A lug-down test on the light-duty diesel vehicle showed a significant reduction in smoke emission coupled with a reduction in power output of the vehicle. It can be concluded that dimethyl carbonate-blended diesel can effectively reduce particulate emission. .

Davidovic, M.; Ferge, T.; Hafner, K.; Maguhn, J.; Muhlberger, F.; Warnecke, R.; Zimmermann, R., 2006, "On-line analysis of gas-phase composition in the combustion chamber and particle emission characteristics during combustion of wood and waste in a small batch reactor," *Environmental Science and Technology*, **39**(6): 1393–1402

The emission of participate matter and gaseous compounds during combustion of wood and refuse-derived fuel in a small batch reactor is investigated by laser mass-spectrometric on-line measurement techniques for gas-phase analysis and simultaneous registration of physical aerosol properties (number size distribution). The gas-phase composition is addressed by a laser-based mass spectrometric method, namely, vacuum-UV single-photon ionization time-of-flight mass spectrometry (VUV-SPI-TOFMS). Particle-size distributions are measured with a scanning mobility particle sizer. Furthermore, a photoelectric aerosol sensor is applied for detection of particle-bound polycyclic aromatic hydrocarbons. The different phases of wood combustion are distinguishable by both the chemical profiles of gas-phase components (e.g., polycyclic aromatic hydrocarbons, PAH) and the particle-size distribution. Furthermore, short disturbances of the combustion process due to air supply shortages are investigated regarding their effect on particle-size distribution and gas-phase composition, respectively. It is shown that the combustion conditions strongly influence the particle-size distribution as well as on the emission of particle-bound polycyclic aromatic hydrocarbons. 66 Refs.

Hung, Hsueh-Fen; Wang, Chiu-Sen, 2006, "Formation of secondary organic aerosols and reactive oxygen species from diluted motorcycle exhaust," *Journal of the Chinese Institute of Chemical Engineers*, **37**(5):491–499

Oxidation of reactive organic gases (ROG) in ambient air produces low-volatility compounds that may condense to form secondary organic aerosols (SOA). Reactive oxygen species (ROS) are also produced in the photochemical reactions involving ROG In the urban atmosphere, the precursors of SOA and ROS primarily come from vehicular emissions. This study aims at investigating the SOA and ROS formation potentials of diluted motorcycle exhaust under UV irradiation. Exhaust samples were obtained from a 124-cc motorcycle engine under idling conditions. Emissions from the tailpipe were directly collected in a Tedlar bag and diluted with filtered air by a ratio of 5. A filter cassette placed upstream of the bag removed particles in the exhaust while the sample was being collected. The sample in the bag was then irradiated by UV light and the number size distribution of aerosol particles was measured at various time intervals using a scanning mobility particle sizer The concentrations of gaseous and particulate reactive oxygen species were also determined at intervals. Under continuous UV irradiation, the particle number concentration in the bag peaked at 2-3 h, while the gaseous ROS concentration peaked at 5-7 h. The peak concentration of gaseous ROS was about one order of magnitude higher than the initial value in the diluted motorcycle exhaust. From the difference between gaseous and total ROS concentrations, it was estimated that about 9.6% (by mole number) of the total ROS was in the particulate phase. The results suggest that diluted motorcycle exhaust has a high potential to form ROS and SOA under UV irradiation.

Mamakos A.; Ntziachristos L.; Samaras Z., 2006, "Evaluation of the Dekati mass monitor for the measurement of exhaust particle mass emissions," *Environmental Science and Technology*, **40**(15): 4739–4745

The Dekati mass monitor (DMM) is an instrument which measures the mass concentration of airborne particles in real time by combining aerodynamic and mobility size particle classification. In this study, we evaluate the performance of the DMM by sampling exhaust from five engines and vehicles of different technologies in both steady-state and transient tests. DMM results are found higher than the filter-based particulate matter (PM) by 39 (plus or minus) 24% (range stands for (plus or minus) one standard deviation) for 62 diesel tests conducted in total and 3% and 14% higher, respectively, in two gasoline tests. To explore whether the difference occurs because of the different measurement principles of DMM and filter-based PM, the DMM operation is replicated over steady-state tests by combining an electrical low-pressure impactor (ELPI) and a scanning mobility particle sizer (SMPS). The correlation of ELPI and SMPS derived mass and filter-based PM is satisfactory (R2 = 0.95) with a mean deviation of 5 (plus or minus) 15%. For the same tests, the correlation of DMM with PM was also high (R2 = 0.95), but DMM exceeded PM by 44 (plus or minus) 23% on average. The comparison of ELPI and SMPS and DMM results reveals that the latter overestimates both the geometric mean diameter and especially the width of the particle mass-weighted size distribution. These findings demonstrate that the statistically significant difference between the DMM and the filter-based PM cannot just originate from the different measurement principles but also from the actual implementation of the combined aerodynamic-mobility measurement in the DMM. Optimizing the DMM will require changes in its design and/or the calculation algorithm to improve the resolution and width of the aerodynamic size distribution recorded.

McMillian, Michael H.; Lawson, Seth A., 2006, "Experimental and modeling study of hydrogen/syngas production and particulate emissions from a natural gas-fueled partial oxidation engine," *International Journal of Hydrogen Energy*, **31**(7): 847–860

In this study, a combustion model was first applied to conditions representing varying compression ratios and equivalence ratios to investigate engine exhaust composition from partial oxidation (POX) of natural gas in reciprocating engines. The model was experimentally validated over a range of equivalence ratios from 1.3 to 1.6 with a spark-ignited single cylinder engine fueled by natural gas. The modeling results matched well with engine gaseous emission data over the experimental range. The model was also extended to higher equivalence ratios to predict H2 and CO production at engine conditions and stoichiometries representative of homogeneous charge compression ignition (HCCI) engine operation. Secondly, over the same experimental range of equivalence ratios, particulate samples were taken to determine both total particulate mass production (g/hph) via gravimetric measurement as well as particle size distribution and loading via a scanning mobility particle sizer (SMPS). While experiments indicate hydrogen yields up to 11% using spark ignition (SI), modeling results indicate that greater than 20% H2 yield may be possible in HCCI operation. Over the experimental range, rich-burn particulate matter (PM) production is no greater than that from typical lean-burn operation. Finally, an energy balance was performed over the range of engine experimental operation.

2005

Aelander, T.; Antikainen, E.; Elonen, E.; Raunemaa, T.; Rautiola, A.; Torkkell, K., 2005, "Particle emissions from a small two-stroke engine: Effects of fuel, lubricating oil, and exhaust after treatment on particle characteristics," *Aerosol Science and Technology*, **39**(2):151–161

The effects of fuel and lubricating oil formulation and exhaust catalytic aftertreatment on physical and chemical characteristics of two-stroke engine exhaust particles were studied. The exhaust particles were produced with a professional chainsaw engine. The employed fuels were a 98-octane oxygenated, low-sulfur, low-aromatic reformulated gasoline, which served as a reference, and a 95-octane nonoxygenated alkylate gasoline that had no aromatics and olefins. The applied lubricating oils were a semisynthetic mineral-based oil and a biodegradable ester-based oil. In total eight fuel–lubricating oil–catalyst combinations were studied. The test runs were conducted on a test bench and exhaust was diluted in a full-flow dilution tunnel. The size and number emissions of the exhaust particles were measured with a scanning mobility particle sizer (SMPS). The organic carbon (OC) and elemental carbon (EC) composition of the particles were analyzed with a thermal–optical transmission analyzer (TOT). In addition, the inorganic ion and metal composition of the particles were quantified, and the gaseous total hydrocarbon (THC), carbon monoxide (CO), and nitrogen oxide (NOx) emissions were measured. The volatility characteristics of the exhaust particles were studied with a thermal desorption unit combined with the SMPS. The particle mass (PM) emissions ranged without catalyst from 2.9 to 3.4 g/kWh and with catalyst from 1.7 to 2.4 g/kWh, the catalytic converter thus reducing PM emissions by 19–50%. Without catalyst the alkylate fuel–biodegradable oil combination gave the highest particle mass emissions, but with catalyst with the same fuel–oil mixture the emissions were the lowest. The count median diameter (CMD) of the particles ranged from 57 to 123 nm. Without catalyst, the alkylate fuel–biodegradable oil combination gave the lowest number emissions, but with catalyst with the same fuel–oil combination the emissions were the highest. The catalytic converter reduced the particle size by 22–56 nm, but it also increased the number emissions by a factor of 1.3–2.6. In thermal analysis 88–98% of the exhaust particle volume proved to be volatile, the solid fraction consisting of elemental carbon and metal residues. With the mineral-based lubricating oil, the metal residues appeared in two modes at the evaporation temperatures of 350°C and higher, while in the particles produced with the biodegradable oil the residues were unimodally distributed.

Bertola, Andrea; Boulouchos, Konstantinos; Kaegi, Ralf; Mathis, Urs; Mohr, Martin, 2005, "Influence of diesel engine combustion parameters on primary soot particle diameter," *Environmental Science and Technology*, **39**(6): 1887–1892

Effects of engine operating parameters and fuel composition on both primary soot particle diameter and particle number size distribution in the exhaust of a direct-injected heavy-duty diesel engine were studied in detail. An electrostatic sampler was developed to deposit particles directly on transmission electron microscopy (TEM) grids. Using TEM, the projected area equivalent diameter of primary soot particles was determined. A scanning mobility particle sizer (SMPS) was used for the measurement of the particle number size distribution. Variations in the main engine operating parameters (fuel injection system, air management, and fuel properties) were made to investigate soot formation and oxidation processes. Primary soot particle diameters determined by TEM measurements ranged from 17.5 to 32.5 nm for the diesel fuel and from 24.1 to 27.2 nm for the water-diesel emulsion fuel depending on the engine settings. For constant fuel energy flow rate, the primary particle size from the water-diesel emulsion fuel was slightly larger than that from the diesel fuel. A reduction in primary soot particle diameter was registered when increasing the fuel injection pressure (IP) or advancing the start of injection (SOI). Larger primary soot particle diameters were measured while the engine was operating with exhaust gas recirculation (EGR). Heat release rate analysis of the combustion process revealed that the primary soot particle diameter decreased when the maximum flame temperature increased for the diesel fuel. 37 Refs.

Blevins, L.G.; Cauley, T.H., 2005, "Fine particulate formation during switchgrass/coal cofiring," *Journal of Engineering for Gas Turbines and Power*, **127**(3):457–463

Experiments to examine the effects of biomass/coal cofiring on fine particle formation were performed in the Sandia Multi-Fuel Combustor using fuels of pure coal, three combinations of switchgrass and coal, and pure switchgrass. For this work, fine particles with aerodynamic diameter between 10 nm and 1 µm were examined. A constant solid-fuel thermal input of 8 kW was maintained. The combustion products were cooled from 1200 to 420^{o}C during passage through the 4.2 m long reactor to simulate the temperatures experienced in the convection pass of a boiler. Fine particle number densities, mass concentrations, and total integrated number and mass concentrations at the reactor exit were determined using a scanning mobility particle sizer. The fine particle number concentrations for cofiring were much higher than those achieved with dedicated coal combustion. However the total integrated mass concentration of particles remained essentially constant for all levels of cofiring from 0% coal to 100% coal. The constant mass concentration is significant because pending environmental regulations are likely to be based on particle mass rather than particle size.

Burtscher, H., 2005, "Physical characterization of particulate emissions from diesel engines: a review," *Journal of Aerosol Science*, **36**(7):896–932

Properties of particles emitted from diesel engines and the consequences of these properties for sampling and measuring the particles are reviewed. The influence of aftertreatment devices such as particle traps and catalytic converters on particle properties is demonstrated. Based on the particle properties and results from health effect studies, requirements to metrics, and measurement systems, for example, for type approval testing, are discussed. This discussion is limited to physical properties. Special attention is given to the volatile fraction. We show that care has to be taken when designing the sampling and dilution system, because this step decisively influences what happens with the volatile material, which may remain in the gas phase, condense on solid particles, or form new particles by nucleation. If nucleation occurs, particles formed in the sampling lines may dominate the particle number concentration. A selection of systems for dilution, conditioning and measuring is shown. Systems to determine number, mass, and surface concentrations, size distributions, and carbon concentration are discussed. The discussion is focused on systems developed or adapted recently for the physical characterization of diesel particles.

Ciatti, Stephen A.; Miers, Scott A.; Ng, Henry K., 2005 "Influence of EGR on soot production in a light-duty diesel engine," *2005 Fall Technical Conference of the ASME Internal Combustion Engine Division*, 415–423

A study to explore the effect of EGR upon combustion in a light-duty automotive style diesel engine was performed. The engine used in this study was a Mercedes 1.7L 4 cylinder, direct injected turbodiesel with a common rail injection system. The engine was operated at 2500 RPM, 50% load, with constant rail pressure and injection duration. An endoscope imaging system built by AVL, called the VisioScope trademark was used to acquire in-cylinder optical images of combustion events. These images were processed to extract soot radiation temperatures and soot volume fraction for each pixel. The results were compared to global engine measurements using piezo-electric pressure transducers, an emissions bench, and a scanning mobility particle sizer (SMPS) to characterize particulates. It was discovered that the optical data correlated well with the global measurements, allowing for in-depth analysis of the mechanisms of emissions formation at three different EGR levels (0%, 10%, 19%). Several conclusions were reached, including the correlation of soot radiation temperature with NO_x production and the correlation of soot luminosity with engine-out PM. Each of these factors was determined as a function of EGR level. 9 Refs.

Ferge, T.; Maguhn, J.; Hafner, K.; Muehlberger, F.; Davidovic, M.; Warnecke, R.; Zimmermann, R., 2005, "On-Line Analysis of Gas-Phase Composition in the Combustion Chamber and Particle Emission Characteristics during Combustion of Wood and Waste in a Small Batch Reactor," *Environmental Science & Technology*, **39**(6):1393–1402

The emission of particulate matter and gaseous compounds during combustion of wood and refuse-derived fuel in a small batch reactor is investigated by laser mass-spectrometric on-line measurement techniques for gas-phase analysis and simultaneous registration of physical aerosol properties (number size distribution). The gas-phase composition is addressed by a laser-based mass spectrometric method, namely, vacuum-UV single-photon ionization time-of-flight mass spectrometry (VUV-SPI-TOFMS). Particle-size distributions are measured with a scanning mobility particle sizer. Furthermore, a photoelectric aerosol sensor is applied for detection of particle-bound polycyclic aromatic hydrocarbons. The different phases of wood combustion are distinguishable by both the chemical profiles of gas-phase components (e.g., polycyclic aromatic hydrocarbons, PAH) and the particle-size distribution. Furthermore, short disturbances of the combustion process due to air supply shortages are investigated regarding their effect on particle-size distribution and gas-phase composition, respectively. It is shown that the combustion conditions strongly influence the particle-size distribution as well as on the emission of particle-bound polycyclic aromatic hydrocarbons.

Giechaskiel, B.; Ntziachristos, L.; Samaras, Z.; Scheer, V.; Casati, R.; Vogt, R., 2005, "Formation potential of vehicle exhaust nucleation mode particles on-road and in the laboratory," *Atmospheric Environment & Atmos. Environ*, **39**(18): 3191–3198

A mobile laboratory equipped with gas analyzers, a particle number counter and a scanning mobility particle sizer was employed to measure the exhaust particle size distributions of a diesel Euro III passenger car, chasing its exhaust plume on a high-speed track at 50, 100 and 120 km/h. Emissions from the same vehicle were also measured in the laboratory under the same driving conditions, using a partial flow sampling system with constant sampling conditions. The vehicle was equipped with an oxidation catalyst and was operated on diesel fuel with 280 ppm wt. sulphur content. Similar results for the exhaust aerosol behaviour were found in both sampling environments, despite the different dilution ratio, sampling temperature and residence time of the aerosol in dilute conditions. A relatively constant soot particle mode was formed in all cases and, in addition, a nucleation mode started to form at 100 km/h and became more stable at 120 km/h. No nucleation mode was observed at 50 km/h road load. The similar behaviour of nucleation mode particles both in the chasing and the laboratory tests indicated that such small volatile particles are a true vehicle emission component and not a dilution artefact. Additional measurements in the laboratory with varying engine load revealed that the nucleation mode formation is sensitive to exhaust gas temperature and its occurrence in increased temperature is repeatable and stable for long sampling times. The findings of this study indicate that nucleation mode particles are an actual emission component of diesel passenger cars and they need to be considered in relevant exhaust aerosol characterization studies.

Johnson, J.P.; Kittelson, D.B.; Savstrom, J.C.; Watts, W.F., 2005, "Influence of a catalytic stripper on the response of real time aerosol instruments to diesel exhaust aerosol," *Journal of Aerosol Science*, **36**(9):1089–1107

The objective of this study was to evaluate the response of a suite of portable, real-time aerosol instruments to Diesel exhaust aerosol with and without a catalytic stripper (CS) to determine the change in response as a function of particle size and volatility. The response of the photoemission aerosol sensor (PAS) was strongly influenced by the physical and chemical nature of Diesel aerosol. The presence of a large, predominantly volatile nuclei mode, and/or the presence of volatile material on the surface of the solid carbonaceous agglomerates in the accumulation mode suppressed the PAS response. Removal of the volatile material by passage of the aerosol through the CS enhanced the response, and improved correlations between the PAS, the diffusion charger (DC) and the scanning mobility particle sizer (SMPS). Data on aerosol size distributions, number, volume, and surface area concentrations with and without the CS in the sample stream are reported. 28 Refs.

Johnson, Jason P.; Kittelson, David B.; Watts, Winthrop F., 2005, "Source apportionment of diesel and spark ignition exhaust aerosol using on-road data from the Minneapolis metropolitan area," *Atmospheric Environment*, **39**(11): 2111–2121

Air quality measurements were made on interstate highways in the Minneapolis metropolitan area. Gas and aerosol concentrations were measured on weekdays and weekends. By exploiting the difference in the relative volumes of heavy duty (HD) diesel and light duty (LD) spark ignition (SI) vehicles on weekdays and weekends, we were able to estimate apportioned fuel specific emissions. The on-road, apportioned, fuel specific particle number emissions factors, estimated from condensation particle counter (CPC) measurements were 1.34±0.2 10^{16}/particles kg^{-1} for diesels and 7.1 ±1.6 10^{15} particles kg^{-1} for spark ignition vehicles. Estimates from the scanning mobility particle sizer (SMPS) measurements were 2.1 ±0.3 10^{15} particles kg^{-1} for diesels and 3.9 ±0.6 10^{14} particles kg^{-1} 3 for SI vehicles. The difference between CPC and SMPS measurements is mainly due to different lower size detection limits of the instruments, similar to 3 and similar to 10 nm, respectively. On a weekly weighted basis and on weekdays, the majority of particle number was attributed to HD diesel traffic. Weekend production of particles can be primarily attributed to light duty SI automobiles. On a per vehicle basis, HD vehicles produced substantially greater numbers of particles. On a fuel specific basis, HD vehicles produce slightly higher concentrations of particles than light duty vehicles. The relative contribution of LD vehicles to particle number emissions increased as particle size decreased. The HD apportioned size distributions were similar to size distributions measured during other on-road and laboratory studies. The LD apportioned size distribution was bounded by laboratory and on-road size distributions. Our work is representative of summer, highway cruise conditions. It is likely that under cold start and high load operating conditions LD emissions will increase relative to HD emissions. 37 Refs.

Johnston, Murray V.; Li, Zhigang; Richter, Henning; Wang, Hai; Yang, Zhiwei; Zhao, Bin, 2005, "Particle size distribution function of incipient soot in laminar premixed ethylene flames: Effect of flame temperature," *Proceedings of the Combustion Institute*, **30**(1): 1441–1448

Particle size distribution functions (PSDFs) of incipient soot formed in laminar premixed 24.2% ethylene-37.9% oxygen-diluent (nitrogen and/or argon) flames with an equivalence ratio of 1.92 were studied by online sampling and scanning mobility particle sizer. Two series of flames were studied to quantify the effect of flame temperature on the characteristics of PSDFs. In the first series, the variation of the flame temperature was accomplished by varying the cold gas velocity. Temperature in the second series of flames was manipulated by the diluent composition from argon to nitrogen. The results show that for flames with the maximum temperature (T/submax/) around 1800 K the soot PSDFs were distinctively bimodal. As the flame temperature was increased to similar to 1850 K, bimodality faded away. The distribution was unimodal for T /submax/ $GRT 1900 K. The variation of the characteristics of the PSDF as a function of the flame temperature is consistent with the theoretical explanation that bimodality is the result of competition between persistent particle nucleation and particle-particle coagulation in low-temperature flames. 34 Refs.

Lee, Byung Uk; Bae, Gwi-Nam; Kim, Jin Kuk; Lee, Jin Ha; Yeo, Gwon-Koo, 2005, "The Behavior of Combustion Aerosols in an Exhaust Pipe," *The 13th International Pacific Conference on Automotive Engineering*, August 22–24, 2005, Seoul, Korea

The diesel particulate filters have been developed to remove diesel particles known to have adverse health effect from the automotive emission. Understanding of the phenomena of diesel exhaust in an exhaust pipe is needed in designing a DPF. In this study, the phenomena of diesel exhaust in an exhaust pipe were simulated by using combustion aerosols. The test aerosols were generated from a combustion aerosol generator consisting of a burner and a dilution unit. Temperature in an exhaust pipe was constantly controlled by using a heating tape. Particle size distributions were measured by a scanning mobility particle sizer. The particle formation and growth will be discussed.

Lipsky, Eric M.; Robinson, Allen L., 2005, "Design and evaluation of a portable dilution sampling system for measuring fine particle emissions from combustion systems," *Aerosol Science and Technology*, **39**(6):542–553

The size and complexity of current dilution samplers is a major barrier to more wide-spread application of these systems for source characterization. A new, more portable dilution sampler has been designed to provide measurements consistent with the widely cited Caltech dilution sampler. Intercomparison experiments were performed using a diesel engine and wood stove to evaluate the comparability of the new design with a sampler based on the Caltech design. These experiments involved simultaneous operation of multiple dilution samplers from the same source. Filter based measurements included PM2.5 mass, organic carbon, and elemental carbon emissions. Particle size distributions in the range from 10-480 nm were measured using a scanning mobility particle sizer.

The filter-based and integrated-total volume measurements made with the two designs are in good agreement. For example, the average relative bias between the two samplers of PM2.5 mass emission rate measured with Teflon filters is 1%. Nucleation was intermittently observed in the sampler based on the Caltech design, but rarely observed in the new design. Significant discrepancies in total number emissions between the two samplers occurred during periods of nucleation. Experiments were also conducted to examine the effects of residence time on the diluted emissions. No changes in the filter-based or integrated volume measurements were observed with an additional 40-s residence time, indicating that phase equilibrium is established in the 2.5 s of residence time provided by the dilution tunnel. This conclusion is consistent with theoretical analysis. These results provide new insight into the effects of dilution sampling on measurements of fine particle emissions, providing important data for the ongoing effort of the EPA and ASTM to define a standardized dilution sampling methodology for characterizing emissions from stationary combustion sources. 20 Refs.

Mathis, U.; Mohr, M.; Kaegi, R.; Bertola, A.; Boulouchos, K., 2005, "Influence of Diesel Engine Combustion Parameters on Primary Soot Particle Diameter," *Environmental Science & Technology*, **39**(6): 1887–1892

Effects of engine operating parameters and fuel composition on both primary soot particle diameter and particle number size distribution in the exhaust of a direct-injected heavy-duty diesel engine were studied in detail. An electrostatic sampler was developed to deposit particles directly on transmission electron microscopy (TEM) grids. Using TEM, the projected area equivalent diameter of primary soot particles was determined. A scanning mobility particle sizer (SMPS) was used for the measurement of the particle number size distribution. Variations in the main engine operating parameters (fuel injection system, air management, and fuel properties) were made to investigate soot formation and oxidation processes. Primary soot particle diameters determined by TEM measurements ranged from 17.5 to 32.5 nm for the diesel fuel and from 24.1 to 27.2 nm for the water-diesel emulsion fuel depending on the engine settings. For constant fuel energy flow rate, the primary particle size from the water-diesel emulsion fuel was slightly larger than that from the diesel fuel. A reduction in primary soot particle diameter was registered when increasing the fuel injection pressure (IP) or advancing the start of injection (SOI). Larger primary soot particle diameters were measured while the engine was operating with exhaust gas recirculation (EGR). Heat release rate analysis of the combustion process revealed that the primary soot particle diameter decreased when the maximum flame temperature increased for the diesel fuel.

Montajir, Rahman M.; Kawai, Terunao; Goto, Yuichi; Odaka, Matsuo, 2005, "Thermal Conditioning of Exhaust Gas: Potential for Stabilizing Diesel Nano-Particles," *SAE World Congress*, April 11–14, 2005, Detroit, Michigan, USA

Conditioning of diluted exhaust gas by Thermo-Conditioner prior to measurement has been proposed by the GRPE/PMP Research Council of the United Nation in order to achieve stability in nano-particle measurement. In this study the effect of thermo-conditioner on the thermo-physical behavior of nanoparticle under different conditions have been clarified. Stability in measurement was also attempted depending on the characteristics of nano-particles. Quality of the raw exhaust gas, the dilution ratio and temperature, and the thermal-conditioning temperature were considered as the main parameters. Exhaust gas from a medium-duty DI diesel engine was used for analysis. Scanning Mobility Particle Sizer was used for measuring the concentration of nano- particles. It was concluded that the concentration of nuclei-mode particles within the size range of 15-30 nm are significantly influenced by the thermal conditioning temperature. However the concentration of accumulation mode particles having the diameter of about 100 nm experiences no influence. Thermal conditioning of exhaust gas at a temperature of over 300oC is assumed to be sufficient for stabilizing the nano-particles. Hot dilution showed better stability in measurement than cold dilution.

Ntziachristos, L.; Pistikopoulos, P.; Samaras, Z., 2005, "Particle characterization from two-stroke powered two-wheelers," *International Journal of Engine Research*, **6**(3):263–275

This paper presents the physical characterization of particle emissions from small two-stroke gasoline two-wheelers. Particle samples were drawn with a dedicated partial dilution system. They were analyzed with various aerosol measurement instruments, including a scanning mobility particle sizer (SMPS), an electrical low-pressure impactor (ELPI), and a diffusion charger. Solid particles were discriminated by using a thermodenuder. Results suggest that small two-wheeled vehicles are significant emitters of both solid and volatile particles with the volatile fraction being the dominant one. The particle size distribution appears bimodal at high load and log-normal at lower load. The high concentration of condensable species in the exhaust also leads to the formation of volatile particles in the accumulation mode, which is typically not observed in diesel exhaust. Further comparison with a typical diesel passenger car revealed that some older technology two-wheelers emit even higher mass and solid particle counts than the car. However, the paper concludes that technology improvements such as oxidation catalysts and direct injection systems are expected significantly to reduce particulate matter emission rates. 20 Refs.

Pagels, Joakum; Wierzbicka, Aneta; Bohgard, Mats; Strand, Michael; Lillieblad, Lena; Sanati, Mehri; Swietlicki, Erik, 2005, "In-Situ Characteristics of Particle Emissions from Biomass Combustion," *Conference: NOSA 2004 Aerosol Symposium: Combustion Aerosols*, Stockholm (Sweden), 11–12 Nov. 2004

In this work we used a Scanning Mobility Particle Sizer and an Electrical Low-pressure Impactor to: a) Derive information of the particle morphology through air-borne analysis and b) Identify time and size variations of particle phase components from incomplete combustion and ash-components. The results presented here covers measurements in two moving grate boilers (12 MW operating on moist forest residue and 1.5 MW operating on wood pellets). We have previously shown that PM1 estimated from Electrical Low-Pressure Impactor (ELPI)-measurements consisted of a rather constant background with peaks correlating with CO and OGC peaks. In the 1.5 MW boiler EC contributed to 34% of PM1, while in the 12 MW boiler EC was below 0.5%. Figure 2 shows time variations in the 1.5 MW boiler as the current in three stages of the ELPI-impactor. Note that time-variations increase strongly with particle size. The fraction of the gravimetric mass detected as water-soluble ions (IC) decreased from ~ 70% for d_{ae}= 78 and 133 nm to ~25% for 322 and 510 nm particles and increased to around 50% for particles larger than 1 µm. In the 12 MW boiler time variations were as low as for 128 nm particles and IC recovery was high for all studied particle sizes. Based on these data we conclude that PM consisting of ash-components are formed with small time variations mainly in mobility-sizes below 250 nm, while Elemental Carbon is emitted at high concentrations during peaks on the time-scale 10-30 s, mainly in particle sizes larger than 150 nm. However, the detailed mixing status of these two particle types/materials is still not known.

Rubino, L.; Phillips, Paul R.; Twigg, Martyn V., 2005, “Measurements of Ultrafine Particle Number Emissions From a Light-Duty Diesel Engine Using SMPS, DMS, ELPI and EEPS,” *7th International Conference on Engines for Automobile*, September 11–16, 2005, Naples, Italy

Tightening of automotive particulate matter (PM) emission regulations, driven by health concerns over ultrafine (< 100 nm) and nano-sized (< 50 nm) particles, has focused attention on measurement of particle size and number at the tailpipes of diesel engines. This study presents an investigation of PM emissions by number from a Light-Duty Diesel Engine running on low sulfur fuel using different aftertreatment systems. PM measurements by number and size were conducted over both transient and steady-state engine conditions using a standard CVS dilution tunnel. A Scanning Mobility Particle Sizer (SMPS), Electrical Low Pressure Impactor (ELPI), Differential Mobility Spectrometer (DMS) and an Engine Exhaust Particle Sizer (EEPS) were used for PM measurements. The performance of each particle size measurement instrument was assessed, and a comparison provided at similar experimental conditions. A standard diesel oxidation catalyst and particulate filters were used as aftertreatment systems. Particle number emissions for each are compared.

Stetter, John C.; Foster, David E.; Schauer, James J., 2005, “Modern Diesel Particulate Matter Measurements and the Application of Lessons Learned to 2007 Levels and Beyond,” *SAE World Congress*, April 11–14, 2005, Detroit, Michigan, USA

Condensation particle counters (CPCs) have been used extensively during the past decade to measure the particle number concentration and, as part of a scanning mobility particle sizer (SMPS(TM)) spectrometer, the size distribution of ultrafine and fine particle emissions from a wide range of spark ignition and diesel engines. This paper illustrates a method of calibrating the CPC particle counting efficiency, determination of the smallest particle size detection limit, and particle concentration linearity, by generating ultrafine particles with a novel, commercially available electrospray aerosol generator and using a sensitive aerosol electrometer as the traceable reference. The counting efficiencies of several TSI model 3010 CPCs were calibrated against the electrometer using monodisperse particles in the size range of 4.5 to 95 nm. Results from the tests show that the counting efficiencies of the CPCs are in close agreement with each other. The concentration linearity response of the CPCs was tested with monodisperse 50 nm particles and compared against the aerosol electrometer at six particle concentration levels roughly equally spaced across the CPCs' measurement range. The test results demonstrate a linear measurement response of each CPC with correlation coefficients (Rsup 2) greater than 0.99. This paper also demonstrates that the lower detection limit of the CPC can be desensitized by adjusting the internal operating parameters of the CPC.

Taishi, Tsuyoshi; Koyama, Tetsuji; Kwon, Soon-Bark; Seto, Takafumi; Sakurai, Hiromu, 2005, “New Measurement System of Nanoparticles in the Automobile Exhaust Gas,” *JSAE Technical Paper No. 20055680, JSAE Autumn Conference*, Sept. 28–30, 2005, Toyoko, Japan

The aerosol measurement techniques such as scanning mobility particle sizer (SMPS) are one of major methods to evaluate the size distribution of diesel nanoparticles. The charge distribution is important to reduce data from mobility distribution to size distribution. The radioactive sources as aerosol charge neutralizer has been widely used, however, the limit of ion generation rate and the difficulty in handling especially at outdoor measurement remained as problem. In this presentation, we developed a new measurement system for diesel nanoparticles using the microplasma aerosol charger. Characteristics and performance of the system for diesel nanoparticle measurement were reported.

Westerdahl, D.; Fruin, S.; Sax, T.; Fine, P. M.; Sioutas, C., 2005, “Mobile platform measurements of ultrafine particles and associated pollutant concentrations on freeways and residential streets in Los Angeles,” *Atmospheric Environment & Atmos. Environ*, **39**(20): 3597–3610

Recent health studies have reported that ultrafine particles (UFP) (<0.1 µm in diameter) may be responsible for some of the adverse health effects broadly attributed to particulate matter. In urban areas, UFP are produced by combustion sources, such as vehicle exhaust, and by secondary formation in the atmosphere. While UFP can be monitored, few studies have explored the impact of local primary sources in urban areas (including mobile sources on freeways) on the temporal and spatial distribution of UFP. This paper describes the integration of multiple monitoring technologies on a mobile platform designed to characterize UFP and associated pollutants, and the application of this platform in a study of UFP number concentrations and size distributions in Los Angeles. Monitoring technologies included two condensation particle counters (TSI Model 3007 and TSI 3022A) and scanning mobility particle sizers for UFP. Real-time measurements made of NO_x (by chemiluminesence), black carbon (BC) (by light absorption), particulate matter-phase PAH (by UV ionization), and particle length (by diffusional charging) showed high correlations with UFP numbers. Average concentrations of UFP and related pollutants varied strongly by location, road type, and truck traffic volumes, suggesting a relationship between these concentrations and truck traffic density.

Zeuthen, Jacob; Livbjerg, Hans, 2005, “Laboratory Investigation of Aerosol Formation in Combustion of Biomass,” *NOSA 2004 Aerosol Symposium: Combustion Aerosols*, Stockholm (Sweden), 11–12 Nov. 2004

In this project the formation of aerosol particles and deposits in power plants during combustion of CO_2-neutral fuels are investigated. For the experimental work a 173 cm long tubular furnace (diam=25 mm) with laminar flow is used. It is possible to control the temperature up to ~ 1200 deg C in nine separate axial sections along the flue gas flow direction. In the first part of the reactor an inner tube is placed. In this inner tube a flow of inert nitrogen passes pellets of inert alumina impregnated with the salt to be volatilized (e.g. NaCl or KCl). The nitrogen gets saturated and by changing the temperature of the pellets it is possible to adjust the salt concentration in the gas. Other reactive gases (SO_2, H_2O, NO and O_2/air) enter the reactor on the outside of the salt-containing alumina pipe. The temperature is kept constant in the first part of the reactor and is then decreased in the flow direction after a given length. The results obtained so far have shown that the homogeneous nucleation rate of pure salts depends on cooling rate, salt concentration and on the vapor pressure of the salt. Examples of results are shown at figure 1a. Here, two identical experiments are performed with two different salts. Since the vapor pressure of KCl is higher than for NaCl at the same temperature, a higher mass concentration of particles is obtained for this salt. Due to a lower salt concentration the number concentration of NaCl particles is higher, but the particles are smaller. The particles are analyzed with a number of instruments, including scanning mobility particle sizer, low pressure cascade impactor and transition electron microscopy. Experiments with introduction of nucleation seeds in the inlet gas have been performed, and it has been found that a suppression of homogeneous nucleation can be observed at rather low number concentrations of seeds. Homogeneous nucleation is favored by rapid cooling and the critical seed concentration for suppression of nucleation is highly dependent on the rate of cooling. Experiments with sulfation of potassium chloride have been performed. By high-temperature filtering it has been found that potassium sulfate is the nucleating agent in aerosol formation during biomass combustion. In the future, the more advanced alkali-sulfur-chloride chemistry will be studied and the mechanisms leading to aerosol formation under biomass combustion conditions in power plants will be studied. The results will be analyzed by model studies including Computational Fluid Dynamics.

2004

Aalto, P.; Hameri, K.; Hillamo, R. E.; Hussein, T.; Keskinen, J.; Makela, T.; Pakkanen, T. A.; Parviainen, H.; Pirjola, L.; Valli, A.; Virtanen, A., 2004, "'Sniffer' - A novel tool for chasing vehicles and measuring traffic pollutants," *Atmospheric Environment*, **38**(22):3625–3635

To measure traffic pollutants with high temporal and spatial resolution under real conditions a mobile laboratory was designed and built in Helsinki Polytechnic in close co-operation with the University of Helsinki. The equipment of the van provides gas phase measurements of CO and NO_x, number size distribution measurements of fine and ultrafine particles by an electrical low pressure impactor, an ultrafine condensation particle counter and a scanning mobility particle sizer. Two inlet systems, one above the windshield and the other above the bumper, enable chasing of different type of vehicles. Also, meteorological and geographical parameters are recorded. This paper introduces the construction and technical details of the van, and presents data from the measurements performed during an LIPIKA campaign on the highway in Helsinki. Approximately 90% of the total particle number concentration was due to particles smaller than 50nm on the highway in Helsinki. The peak concentrations exceeded often 200,000 particles/cm^3 and reached sometimes a value of 10^6 particles/cm.^{3} Typical size distribution of fine particles possessed bimodal structure with the modal mean diameters of 15-20nm and similar to 150nm. Atmospheric dispersion of traffic pollutions were measured by moving away from the highway along the wind direction. At a distance of 120-140m from the source the concentrations were diluted to one-tenth from the values at 9m from the source. 25 Refs.

Abu-Allaban, M.; Gertler, A. W.; Rogers, C. F., 2004, "A Quantitative Description of Vehicle Exhaust Particle Size Distributions in a Highway Tunnel," *Journal of the Air and Waste Management Association*, **54**(3):360–366

During the period May 18-May 22, 1999, a comprehensive study was conducted in the Tuscarora Mountain Tunnel on the Pennsylvania Turnpike to measure real-world motor-vehicle emissions. As part of this study, size distributions of particle emissions were determined using a scanning mobility particle sizer. Each measured size distribution consisted of two modes: a nucleation mode with midpoint diameter less than 20 nm and an accumulation mode with midpoint diameter less than 100 nm. The nucleation and accumulation components in some distributions also exhibited second maxima, which implies that such particle size distributions are superpositions of two particle size distributions. This hypothesis was utilized in fitting the particle size distributions that exhibited second maxima with four lognormal distributions, two for the nucleation mode and two for the accumulation mode. The fitting assumed that the observed particle size distribution was a combination of two bimodal log-normal distributions, one attributed to the heavy-duty diesel (HDD) vehicles and another attributed either to a different class of HDD vehicles or to the light-duty spark ignition vehicles. Based on this method, estimated particle production rates were 1.8×10^{13} and 2.8×10^{14} particles/vehicle-km for light-duty spark ignition and HDD vehicles, respectively, which agreed with independently obtained estimates. 18 Refs.

Aelander, T. J. A.; Leskinen, A. P.; Rantanen, L.; Raunemaa, T. M., 2004, "Characterization of diesel particles: effects of fuel reformulation, exhaust aftertreatment, and engine operation on particle carbon composition and volatility," *Environmental Science and Technology*, **38**(9):2707–2714

Diesel exhaust particles are the major constituent of urban carbonaceous aerosol being linked to a large range of adverse environmental and health effects. In this work, the effects of fuel reformulation, oxidation catalyst, engine type, and engine operation parameters on diesel particle emission characteristics were investigated. Particle emissions from an indirect injection (IDI) and a direct. injection (DI) engine car operating under steady-state conditions with a reformulated low-sulfur, low-aromatic fuel and a standard-grade fuel were analyzed. Organic (OC) and elemental (EC) carbon fractions of the particles were quantified by a thermal-optical transmission analysis method and particle size distributions measured with a scanning mobility particle sizer(SMPS). The particle volatility characteristics were studied with a configuration that consisted of a thermal desorption unit and an SMPS. In addition, the volatility of size-selected particles was determined with a tandem differential mobility analyzer technique. The reformulated fuel was found to produce 10-40% less particulate carbon mass compared to the. standard fuel. On the basis of the carbon analysis, the organic carbon contributed 27-61% to the carbon mass of the IDI engine particle emissions, depending on the fuel and engine operation parameters. The fuel reformulation reduced the particulate organic carbon emissions by 10-55%. In the particles of the DI engine, the organic carbon contributed 14-26% to the total carbon emissions, the advanced engine technology, and the oxidation catalyst, thus reducing the OC/EC ratio of particles considerably. A relatively good consistency between the particulate organic fraction quantified with the thermal optical method and the volatile fraction measured with the thermal desorption unit and SMPS was found. 34 Refs.

Andersson, Jon; Preston, Hugh; Warrens, Chris; Brett, Peter, 2004, "Fuel and lubricant effects on nucleation mode particle emissions from a Euro III light-duty diesel vehicle," *Spring Fuels and Lubricants Conference and Exhibition*, June 8–10, 2004, Toulouse, France

The impact of lubricant sulfur and phosphorus levels on the formation of nucleation mode particles was explored in a light-duty diesel vehicle operating over the New European Drive Cycle (NEDC). All measurements were undertaken using a Scanning Mobility Particle Sizer (SMPS), sampling from a conventional Constant Volume Sampler (CVS) system. Rigorous sampling system and vehicle conditioning procedures were applied to eliminate oil carry-over and nanoparticle artifact formation.
An initial vehicle selection process was undertaken on vehicles representing three fuel injection strategies, namely; distributor pump, common rail and unit injector. The vehicles met Euro III specifications and were all equipped with oxidation catalysts. Idle and low load stability were key requirements, since these conditions are the most significant in terms of their propensity to generate nucleation mode particles.

The influence of fuel sulfur on nucleation particle generation is well documented and three fuels were tested at idle to confirm the chosen vehicle's response to fuel sulfur. Traditional European fuels exhibited strong nucleation modes, with the 50 ppm S fuel showing \mA12% greater nucleation mode levels than the 10 ppm S fuel. Swedish Class 1 Diesel (SWCL1) fuel gave a very stable nucleation particle mode, but at a lower level. This fuel was selected for the lubricant effect study since it was believed that its reduced final boiling point would not overlap with or interfere with the oil discrimination phase of the work.

A total of 9 oils were tested with sulfur and phosphorus levels ranging from 0 to 0.9 and 0 to 0.1%wt respectively. All the oils were fully formulated having SAE "X"W-30 viscosities and a targeted ACEA A5/B5 performance level. Test order was carried out under strict statistical control.

Oil-derived sulfur and phosphorus were both found to increase the production of nucleation mode particles. Little effect of lubricant formulation on accumulation mode particles was observed. Swedish Class 1 (SWCL1) diesel fuel provided substantial reductions in nucleation mode particles.

Bermudez, V.; Desantes, J.M.; Fuentes, E.; Pastor, J.V., 2004, "Methodology for measuring exhaust aerosol size distributions from heavy duty diesel engines by means of a scanning mobility particle sizer," *Measurement Science and Technology*, **15**(10):2083–2098

A study of the sources of variability in particle size measurements using a dilution minitunnel and a scanning mobility particle sizer (SMPS) has been conducted in order to obtain a comprehensive and repeatable methodology that can be used for measuring the particle size distribution of the exhaust aerosol emitted by a heavy duty diesel engine. The paper includes three experimental phases: an experimental analysis of the SMPS operating parameters' influence; an evaluation of the effect of dilution conditions, such as the dilution ratio and the dilution residence time; and a study of the influence of sampling factors, such as measurement stabilization and the effect of exhaust system pre-conditioning. An examination of the type and degree of influence of each studied factor is presented, recommendations for reducing variability are given and critical parameter values are identified to develop a measurement methodology of low uncertainty that could be applied to a further study concerning the effect of engine operating parameters on the exhaust particle size distribution.

Chang, M.-C. O.; Chow, J. C.; England, G. C.; Hopke, P. K.; Watson, J. G.; Yi, S.-M., 2004, "Measurement of ultrafine particle size distributions from coal-, oil-, and gas-fired stationary combustion sources," *Journal of the Air and Waste Management Association*, **54**(12):1494–1505

A dilution chamber was deployed to sample exhaust from a pilot-scale furnace burning various fuels at a nominal heat input rate of 160 kW/h and 3% excess oxygen. The formation mechanisms of particles smaller than 420 nm in electrical mobility diameter were experimentally investigated by measurement with a Scanning Mobility Particle Sizer (SMPS) as a function of aging times, dilution air ratios, combustion exhaust temperatures, and fuel types. The measured particle size distributions in number concentrations measured show peaks of particle number concentrations for medium sulfur bituminous coal, No. 6 fuel oil, and natural gas at 40-50 nm, 70-100 nm, and 15-25 nm, respectively. For No. 6 fuel oil and coal, the particle number concentration is constant in the range of a dilution air ratio of 50, but the number decreases as the dilution air ratio decreases to 10. However, for natural gas, the particle number concentration is higher at a dilution air ratio of 10 and decreases at dilution air ratios of 20-50. Samples taken at different combustion exhaust temperatures for these fuel types show higher particle number concentrations at 645 K than at 450 K. As the aging time of particles increases, the particles increase in size and the number concentrations decrease. The lifetimes of the ultrafine particles are relatively short, with a scale on the order of a few seconds. Results from this study suggest that an aging time of 10 sec and a dilution air ratio of 20 are sufficient to obtain representative primary particle emission samples from stationary combustion sources. 38 refs.

Corporan, E.; DeWitt, M.; Wagner, M., 2004, "Evaluation of soot particulate mitigation additives in a T63 engine," *Fuel Processing Technology*, **85**(6-7):727–742

The performance of fuel additive candidates to mitigate soot particulate emissions in turbine engines was assessed in a T63 helicopter engine. Seventeen additives, including commercial compounds to reduce emissions in internal combustion engines, diesel cetane improvers, and experimental/proprietary additives, were evaluated. The additives were individually injected into the JP-8 fuel feed to the engine, and evaluated at a minimum of three concentration levels. The engine was operated at two conditions, idle and cruise, to investigate additive effects at different power settings or equivalence ratios. Particulate samples were collected from the engine exhaust using an oil-cooled probe, and analyzed using a suite of particulates instrumentation, which included a condensation nuclei counter (CNC), scanning mobility particle sizer (SMPS), laser particle counter (LPC) and a tapered element oscillating microbalance (TEOM). Results indicate that the diesel cetane improvers and commercial smoke abatement additives tested had minimal impact on particulate emissions in the T63 turboshaft engine. One proprietary additive was shown to reduce particle number density (PND) by up to 67% at the relatively high concentration of 3000 mg/l. These benefits were observed only at cruise condition, which may provide some insight into the mechanisms by which the additive suppresses the formation or enhances the oxidation of soot particles. Test results with blends of JP-8 and Norpar-13 (normal paraffins) show significant reductions in particulate emissions for both idle and cruise conditions demonstrating the potential environmental benefits of using blends of clean (low aromatic and low sulfur) fuels with JP-8. Comparisons of mass determination with different instruments and preliminary results of chemical characterization of particulate emissions with and without additives are also presented. 16 Refs.

Cromas, J.; Ghandhi, J. B., 2004, "Lubricating Oil Contribution to Direct-Injection, Two-Stroke Engine Particulate Emissions," *Small Engine Technology Conference*, September 27–30, 2004, Graz, Austria

Particulate emission measurements were performed on a direct-injection, two-stroke engine that employed a lost-oil lubricating system. The particulate emissions were sampled using a partial-flow dilution system. Particulate mass emission rates were measured using a tapered element microbalance (TEOM), and the results were found to compare favorably with gravimetric tests performed simultaneously. The size distribution was measured using a scanning mobility particle sizer (SMPS), and the cumulative mass from the measured size distribution was found to agree well with the values measured by the TEOM. The particulate mass emissions were found to be dominated by particulate matter derived from the engine oil. The particulate emissions were found to decrease substantially as the oil flow to the engine was reduced from the baseline case of 1:100 (oil-to-fuel mass ratio). Additionally, the reduction of the oil flow from the baseline case coincided with the removal of a secondary peak centered at 70 nm in the particle size distribution. It was determined that the oil flow rate had to be decreased to 1:450 in order for trends in the combustion-derived particulate matter to be observable. This level is comparable to levels seen in automotive four-stroke engines.

Hasegawa, S.; Hirabayashi, M.; Kobayashi, S.; Kondo, Y.; Moriguchi, Y.; Tanabe, K.; Wakamatsu, S., 2004, “Size distribution and characterization of ultrafine particles in roadside atmosphere,” *Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering*, **39**(10):2671–2690

The number concentration and number size distributions of ultrafine particles were measured with a Scanning Mobility Particle Sizer (SMPS) at a roadside in early autumn and winter, and the results are discussed with regard to the contribution of traffic activity and meteorological conditions. The number concentration of the <50 nm fraction increased in the morning under calm wind conditions, and this increase corresponded with the increase in total traffic volume and nitric oxide. The increase in ultrafine particles was influenced not only by the increase in total traffic but also by the high contribution of diesel engine vehicles. The number concentration decreased around noon as the wind speed increased, although the total traffic and the number of diesel engine vehicles were at the same level as in the morning. The number size distribution in the morning was bimodal, with a first peak diameter of around 30 nm and a second of around 90 nm in both periods. The volatility of ultrafine particles was investigated using a thermal denuder operating at 250 degrees C. The first peak consisted mainly of volatile components, whereas the second one consisted of solid materials plus some volatile components. These results were consistent with the mass size distribution of elemental and organic carbon. The number size distribution with a peak diameter of around 30 nm was also observed in the afternoon at a suburban site; however, it was produced not by vehicle emissions directly but by photochemical reactions. Although a relatively high number concentration was also observed in the morning at the suburban site due to vehicle emission, the peak diameter ranged from 40 to 90 nm, which was larger than at the roadside.

Haupt, Dan; Nord, Kent; Tingvall, Bror; Ahlvik, Peter; Egeback, Karl-Erik; Andersson, Soren; Blomquist, Micael, 2004, “Investigating the potential to obtain low emissions from a diesel engine running on ethanol and equipped with EGR, catalyst and DPF,” *Spring Fuels and Lubricants Conference and Exhibition*, June 8–10, Toulouse, France

Experiments were performed to investigate the potential to achieve low emissions from a diesel engine fueled by ethanol and equipped with a commercially available exhaust after-treatment device, DNO_x(TM) from STT Emtec. The $DNOsub_x$(TM) system includes exhaust gas recirculation (EGR) catalysts and a continuously regenerating diesel particulate filter (DPF). Two Euro III classified 9-liter turbocharged, after-cooled diesel engines from Scania were used for the task. One engine was fueled by ethanol and the other by Swedish diesel fuel, EC1. Engine operating conditions of a 22-mode test cycle, including the 13 modes of the European Stationary Cycle (ESC cycle), were used for the tests. The emissions of NO_x and HC were small for the ethanol-fueled engine, 3.48 and 0.53 g/kWh, respectively, while the emission of CO was higher, 2.07 g/kWh. Estimations of emitted particle mass were calculated by using the software supplied in the Scanning Mobility Particle Sizer (SMPS). The estimations showed that the ethanol engine emitted only ~1/10 of the particle mass emitted by the diesel-fueled engine. A powerful reduction of the regulated emissions was obtained when equipping the ethanol engine with EGR, catalyst and DPF. The emissions of HC, CO and NO_x decreased down to 0.15, 0.04 and 2.54 g/kWh, respectively, while the estimated particle mass was reduced by 67%. Actually, by using the aftertreatment system, the engine became a Euro IV engine regarding the emissions of HC, CO and NO_x. The system worked even better with the diesel-fueled engine. The NO_x emission was reduced by approximately 33% and the estimated particle mass by more than 99%. Calculations showed that the EGR ratio was higher for the diesel engine than for the ethanol engine. Consequently, by applying a higher EGR ratio for the ethanol engine an additional reduction of the NO_x emissions should be obtained. The results indicate that very low NO_x and particle emissions could be obtained for an ethanol-fueled diesel engine by using the right aftertreatment equipment. Future studies should investigate the possibility to increase the EGR ratio further. The investigations also underline the need for development of a special particulate filter for ethanol engines.

Hosoya, Mitsuru; Shundo, Seiji; Shimoda, Masatoshi, 2004, “The study of particle number reduction using after-treatment systems for a heavy-duty diesel engine,” *SAE 2004 World Congress and Exhibition*, March 8–11, 2004, Detroit, Michigan, USA

To reduce ultra-fine particle number concentration from a heavy-duty diesel engine, the effects of diesel fuel property and after-treatment systems were studied. The reduction of ultra-fine particle number concentration over steady state mode using an 8-liter turbocharged and after-cooled diesel engine was evaluated. PM size distribution was measured by a scanning mobility particle sizer (SMPS). The evaluation used a commercially available current diesel fuel (Sulfur Content: 0.0036 wt%), high-sulfur diesel fuel (Sulfur Content: 0.046 wt%) and low-sulfur diesel fuel (Sulfur Content: 0.007 wt%). The after-treatment systems were an oxidation catalyst, a wire-mesh-type DPF (Diesel Particle Filter) and a wall-flow type catalyzed DPF. The results show that fine particle number concentration is reduced with a low-sulfur fuel, an oxidation catalyst, a wire-mesh-type DPF (Diesel Particulate Filter) and wall-flow-type catalyzed DPF, respectively. The wall-flow=type catalyzed DPF was the most effective for the particle reduction. The particle number reduction efficiency of the wall-flow-type DPF was 97% in the range of 50 to 70 nm mobility diameter over steady state mode.

Johnson, Tim; Caldow, Robert; Poecher, Arndt; Mirme, A.; Kittelson, David, 2004, “A new electrical mobility particle sizer spectrometer for engine exhaust particle measurements,” *SAE 2004 World Congress and Exhibition*, March 8–11, 2004, Detroit, Michigan, USA

Electrical mobility has a long history as a tool for measuring the particle size of engine exhaust emissions. This paper gives a review of these methods as well as more current methods for making exhaust particle measurements. Each of the methods discussed has a limitation especially for making fast (sub-second) measurements. A new instrument is discussed that has been developed by TSI based on a technique developed over the last two decades by the University of Tartu - Estonia. A description of the instrument, the Engine Exhaust Particle Sizer(TM) (EEPS(TM)), is given as well as engine dynamometer data showing a comparison between the current standards for engine exhaust measurements, the Scanning Mobility Particle Sizing (SMPS(TM)) system and the Condensation Particle Counter (CPC). The EEPS compares favorably with the SMPS and CPC while providing sub-second response.

Kaegi, R.; Mathis, U.; Mohr, M.; Zenobi, R., 2004, "TEM analysis of volatile nanoparticles from particle trap equipped diesel and direct-injection spark-ignition vehicles," *Atmospheric Environment*, **38**(26):4347–4355

We investigated volatile nanoparticles emitted from two light-duty vehicles using a transmission electron microscope (TEM). Elemental analysis was performed with an energy dispersive system (EDS) attached to the microscope. Differences in stability of volatile nanoparticles during TEM analysis indicated two different chemical compounds. The results are consistent with the thesis that volatile nanoparticles are composed of a more volatile hydrophilic and a less volatile hydrophobic part. Sulfur and potassium were detected in volatile nanoparticles. These elements are likely to play an important role in the formation of volatile nanoparticles. Particle number size distributions derived from a scanning mobility particle sizer (SMPS) and from TEM image analysis were in good agreement. 42 Refs.

Kawano, Daisuke; Kawai, Terunao; Naito, Hiroyoshi; Goto, Yuichi; Odaka, Matsuo; Bachalo, William D., 2004, "Comparative measurement of nano-particulates in diesel engine exhaust gas by laser-induced incandescence (LII) and scanning mobility particle sizer (SMPS)," *Spring Fuels and Lubricants Conference and Exhibition*, June 8–10, Toulouse, France

Particulate Matter (PM) from diesel engines is thought to be seriously hazardous for human health. Generally, it is said that the hazard depends on the total number and surface area of particles rather than total mass of PM. In the conventional gravimetric method, only the total mass of PM is measured. Therefore, it is very important to measure not only the mass of PM but also size and number density of particulates. Laser-Induced Incandescence (LII) is a useful diagnostic for transient measurement of soot particulate volume fraction and primary particle size. On the other hand, Scanning Mobility Particle Sizer (SMPS) is also used to measure the size distribution of soot aggregate particulates at a steady-state condition. However, the measurement processes and the phenomena used to acquire the information on soot particulate are quite different between the LII and SMPS methods. Therefore, it is necessary to understand the detailed characteristics of both LII and SMPS. In the present study, the size distributions of PM from DI diesel engine are measured by both LII and SMPS simultaneously. In addition, PM mass emission is measured gravimetrically through a dilution tunnel and is separated into SOF and ISOF. The effects of EGR rate and engine load on the results of these particulate measurements are investigated. The different trends in the characteristics of PM emission are shown in each measurement methods for PM. The difference of detailed characteristics between LII and SMPS are illustrated by comparing the measurement results for the particulates. Finally, the problems associated with the measurements using each method are considered and some recommendations have been given for accurate measurement of nanoparticles.

Khatchikian, Peter; Harndorf, Horst; Knopf, Martin, 2004, "Dependence of the Particle Size Distribution on the Injection Pressure of a Modern Diesel Engine With a 1600 Bar Common-Rail Injection System," *2004 FISITA World Automotive Congress*, May 23–27, 2004, Barcelona, Spain

The influence of the injection pressure on the particle size distribution was measured with a scanning mobility particle sizer. Measurements were carried out on a stationary test bench with a 3-l, 6- cylinder, common-rail direct injection engine from a passenger car, by varying the pressure in the rail. The sulfur content of the diesel fuel was < 10 ppm, and the sampling point was the tailpipe or the outlet of a transfer line. First of all, the size distribution was measured with the standard engine calibration. In a second step, only the torque was set to the value of the original operating point (the one with the original rail pressure, etc.) after changing the pressure. This was done by adapting the end of injection. In a third step, the engine was set to the emissions level of the original calibration by varying the EGR rate to set the soot emission (measured in terms of the Bosch Smoke Number, SN), and the start of injection for the NOx level. Finally, the size distribution was measured in this configuration but with the sampling point at the outlet of a transfer line. If the original injection pressure of 550 bar is varied in a range of 250-1600 bar and the engine torque is kept at 82 Nm, a slight decrease in the count median diameter (CMD) with increasing rail pressure can be found; on the other hand, the total number concentration (N) is reduced quite significantly. In the step three configuration, the same emissions as the original calibration, both particle size and concentration are almost constant with changing injection pressure. If the residence time of the aerosol prior to dilution is increased by employing a transfer line, a smaller number of slightly larger particles can be measured. With the test procedure and measurement conditions used in this investigation, no negative effect of high injection pressure on the particle size distribution could be found.

King, C. J.; Linak, W. P.; Miller, C.A.; Santoianni, D. A.; Seo, Y.-C.; Shinagawa, T.; Wendt, J. O. L.; Wood, J. P.; Yoo, J.-I., 2004, "High temperature interactions between residual oil ash and dispersed kaolinite powders," *Aerosol Science and Technology*, **38**(9):900–913

The potential use of sorbents to manage ultrafine ash aerosol emissions from residual oil combustion was investigated using a downfired 82 kW laboratory-scale refractory-lined combustor. The major constituents were vanadium (V), nickel (Ni), iron (Fe), and zinc (Zn). The overall ash content of residual oil is very low, resulting in total ash vaporization at 1725 K with appreciable vaporization occurring at temperatures as low as 1400 K. Therefore, the possibility of interactions between ash vapor and sorbent substrates exists. Kaolinite powder was injected at various locations in the combustor. Ash scavenging was determined from particle size distributions (PSDs) measured by a Scanning Mobility Particle Sizer. Impactor samples and X-ray fluorescence (XRF) analyses supported these data. Injection of kaolinite sorbent was able to capture up to 60% of all the ash in the residual fuel oil. However, captures of ~30% were more common when sorbent injection occurred downstream of the combustion zone, rather than with the combustion air into the main flame. Without sorbent addition, baseline measurements of the fly ash PSD and chemical composition indicate that under the practical combustion conditions examined here, essentially all of the metals contained in the residual oil form ultrafine particles (<0.1 μm diameter). Theoretical calculations showed that coagulation between the oil ash nuclei and the kaolinite sorbent could account for, at most, 17% of the metal capture which was always less than that measured. The data suggest that kaolinite powders reactively capture a portion of the vapor phase metals. Mechanisms and rates still remain to be quantified.

Liu, MA; Cheung, C S; Pan, KY, 2004, "Effect of Oxygenated Additive on Particle Emission from Diesel Engine," *Journal of Air Force Engineering University (Natural Science Edition) (China)*, **5**(3):71–74

The effect of oxygenated additive on particle emission is investigated. Particle size distribution in exhausts from a diesel engine fueled by the blended fuel with different proportion of oxygenated additive are measured by a scanning mobility particle sizer and an aerodynamic particle sizer. Coupled with this, emissions of carbon monoxide, hydrocarbon and nitrogen oxide are also measured with an infrared analyzer, a flame ionization detector and a chemiluminiscent analyzer respectively. Results show that there is an effect of oxygenated additive on the particle size distribution from diesel engine. Oxygenated additive can significantly reduce particle emission level and slightly modify emission concentrations of carbon monoxide, hydrocarbon and nitrogen oxide.

Lyyränen, Jussi; Jokiniemi, Jorma; Kauppinen, Esko; Backman, U.; Vesala, Hannu, 2004, “Comparison of Different Dilution Methods for Measuring Diesel Particle Emissions,” *Aerosol Science & Technology*, **38**(91):12–23

Particle emissions from a turbo-charged diesel off-road engine were characterized with DMA + CNC and electron microscopy for comparison of different sampling and dilution systems. Four different sampling methods were used: (1) two ejector diluters, (2) partial flow and ejector diluter, (3) porous tube and ejector diluter, and (4) porous tube diluter. Number size distributions for partial flow and ejector dilution had modes at 25–30 nm and at 45–50 nm independent of the dilution ratio. The mode at 25–30 nm indicated nucleation during dilution in these experiments and was clearly most significant for the partial flow and ejector diluter setup. This was attributed to the temperature difference between exhaust gas, sample line, and partial flow diluter and cold dilution air. For other dilution systems the main mode was at 45 nm and indications of a mode at 15–20 nm were observed depending on the dilution ratio. Especially for the porous tube diluter, the main mechanism for particle growth was condensation on the surfaces of the existing particles. According to this study the best dilution system for obtaining a number size distribution without any significant nucleation effects was the porous tube dilution setup.

Nord, Kent; Haupt, Dan; Ahlvik, Peter; Egeback, Karl-Erik, 2004, “Particulate emissions from an ethanol-fueled, heavy-duty diesel engine equipped with EGR, catalyst and DPF,” *Spring Fuels and Lubricants Conference and Exhibition*, June 8–10, 2004, Toulouse, France

Ethanol-fueled engines are considered to be low particulate-emitting engines. This study was performed to investigate the potential to achieve even lower particulate emission if a 9-liter Scania diesel engine, running on ethanol fuel is equipped with emission control. State-of-the-art technology in emission control was applied, e.g., exhaust gas recirculation, EGR, catalysts and a continuous regenerating particle filter, DPF. Particulate emissions were compared with emissions from a 9-liter Scania diesel engine from the same engine family, running on Swedish environmental class 1 diesel fuel. Tailpipe measurements of particle size and distribution were performed with a scanning mobility particle sizer, SMPS, instrument together with filter sampling. An evaluation of SMPS measurements was performed for test conditions specified according to a 22-mode test cycle, which included the test modes in the European Stationary Cycle, ESC. Calculated weighted particle mass from SMPS data, and in accordance with ESC, showed that the ethanol engine without emission control emitted approx. 1/12 of particle mass compared to the diesel engine. Weighted particulate emissions were reduced by approx. 96%, when the engine was fitted with EGR and DPF. The reduction of weighted particulate emissions was even higher when the diesel engine was fitted with EGR and DPF, as high as 99%. Particle size and distribution measurements revealed that particles emitted from the ethanol engine mainly consisted of ultrafine particles (<100 nm), usually had a mean diameter of about 30 nm, while particles emitted from the diesel engine usually had mean diameters of about 60-70 nm and sizes going up to approx. 300 nm. Filter samples analyzed by Scanning electron microscopy and energy dispersive x-ray analysis SEM/EDX showed that the particles, both from the ethanol-fueled engine and the diesel-fueled engine mainly consisted of carbon and that they agglomerated, dependent upon running conditions, chainlike or clot-wise. Raman spectroscopy confirmed that the same elemental carbon was present in particles emitted from diesel and ethanol-fueled engines. The investigations showed that the system used, with EGR and DPF combined, is highly effective in reducing particulate emissions from ethanol- and diesel-fueled diesel engines. A general conclusion is also that the ethanol-fueled engine, equipped with emission control system or not, emitted lower particle mass, smaller particle sizes and approx. the same or a greater number of particles in the emissions than the diesel-fueled engine.

Van Gulijk, C., Marijnissen, J.C.M., Makkee, M., Moulijn, J.A., Schmidt-Ott, A., 2004, “Measuring diesel soot with a scanning mobility particle sizer and an electrical low-pressure impactor: performance assessment with a model for fractal-like agglomerates,” *Journal of Aerosol Science*, **35**:633–655

The scanning mobility particle sizer (SMPS) and the electrical low-pressure impactor (ELPI) are frequently used to measure particle size distributions of combustion aerosols. The instruments are especially popular for diesel exhaust measurements since the emission of "particulate matter" is restricted by legislation. A problem is that the interpretation of the results that these instruments give is not straightforward: fractal-like diesel soot agglomerates in the exhaust have a complex interaction with their carrier gas. This paper focuses on this complex interaction in order to assess its effect on the instruments' output. A theoretical model for the aerodynamic behavior of fractal-like agglomerates is used as a tool to assess the performance of the ELPI and the SMPS for the measurement of diesel soot particles. The model couples the aerodynamic diameter and the mobility diameter for fractal-like soot agglomerates. Visual analysis with scanning electron microscopy (SEM) aids model development and instrument performance assessment. It is concluded that the performance of both instruments is affected by the fractal-like structure of diesel soot. The ELPI, if it is set to measure the aerodynamic diameter, gives an underestimation of the apparent size of particles due to their fractal-like structure. As a result, the number of particles is overestimated. The model presented in this paper helps interpretation of the ELPI's response. The SMPS is affected by multiple charging of soot agglomerates, larger than 1000 nm, which are abundantly present in diesel exhaust gas and are not removed by the impaction stage at the input due to their small effective density. The diesel engine in this paper emits many of such particles. Multiple charging leads to an underestimation of the size of the agglomerates and hampers size classification in the instrument. (author)

Zervas, Efthimios; Dorlhene, Pascal; Daviau, Richard; Dionnet, Bernard, 2004, “Repeatability of fine particle measurement of diesel and gasoline vehicles exhaust gas.” *Spring Fuels and Lubricants Conference and Exhibition*, June 8–10, 2004, Toulouse, France

Four diesel vehicles and two gasoline ones are used to determine the repeatability of the particle number and size measurements. Two analytical techniques are used: Scanning Mobility Particle Sizer (SMPS) and Electrical Low Pressure Impactor (ELPI). The influence of technology (Euro2 and Euro3, diesel and gasoline vehicles, Diesel Particulate Filter (DPF), Gasoline Direct Injection (GDI)) and speed on the particle number and size is presented in the case of steady speeds and the European Driving Cycle (EDC). The repeatability of these measurements is determined at the entire particle distribution. The global 1.96*Standard Deviation (SD) of the median diameter, determined by SMPS, is 8 nm. The median diameter is difficult to be determined in several cases due to the flat profiles of the emitted particles. The global 1.96*Relative Standard Deviation (RSD) of the particle number presents a U-like curve, with a minimum value (55-57%) at about 100 nm. These values can reach the 180% (ELPI) and 280% (SMPS) at the extremes of this curve.

Zhao, Bin; Yang, Zhiwei; Li, Zhigang; Johnston, M. V.; Wang, Hai. 2004, "Particle size distribution function of incipient soot in laminar premixed ethylene flames: effect of flame temperature," *Proceedings of the Combustion Institute*, **30**: 1441–1448

2003

Aigner, M.; Wahl, C., 2003, "Aircraft gas turbine soot emission tests under technical relevant conditions in an altitude test facility and validation of soot measurement technique," *American Society of Mechanical Engineers, International Gas Turbine Institute, Turbo Expo (Publication) IGTI*, **1**:189–200

An aircraft gas turbine was tested in an altitude test facility under technical relevant flight conditions. Test points are the ICAO power settings IDLE, TAKE OFF, CLIMB and DESCENT, as well as CRUISE conditions. The used measurement techniques are Scanning Mobility Particle Sizer (SMPS) 1 and Scanning Electron Microscopy (SEM). It is shown, that the relative Soot Emission Index (compared to take off conditions) is increasing with power setting. The mean diameter of the particles is also increasing with power setting. The particles show a lognormal size distribution for most of the test points. Under TAKE OFF conditions (100% power setting) we found a bimodal size distribution. The SEM pictures show the fractal character of the soot particles with 10 to 15nm primary particles as well as the agglomerates. To validate the measurement techniques a variable soot generator 2 for nanoparticles was developed. This soot generator was used to check sample line losses. In an additional experiment we used this soot generator to test the trapping efficiency of the recommended filters for the so called ICAO Smoke Number which is the same as SAE- Smoke Number 3 or EPA - Smoke Number 4 . 11 Refs.

Ayala, Alberto; Olson, Bernard; Cantrell, Bruce; Drayton, Marcus; Barsic, Nicholas, 2003, "Estimation of diffusion losses when sampling diesel aerosol: A quality assurance measure," *JSAE Technical Paper No. 20030138, 2003 JSAE/SAE International Spring Fuels and Lubricants Meeting*, May 19–22, 2003, Yokohama, Japan

Under the sponsorship of the Coordinating Research Council (CRC), the University of Minnesota (UMN) formed an international research team to investigate the physical and chemical nature of diesel emissions from heavy duty vehicles while operating on highways (CRC Project E-43). These ambient measurements of vehicle emissions following their release into and dilution by the atmosphere guided the development of dilution and sampling procedures for laboratory test cells to simulate on-highway conditions. The importance, visibility, and potential implications of the project prompted the adoption of a quality assurance (QA) plan by an independent implementation team. Because exhaust aerosol characterization for mobile sources lacks prescribed sampling methodologies, standard operating procedures were developed as part of the QA effort to ensure the consistency and validity of the data collected. To verify the daily protocols used, the QA team made surveillance visits to observe UMN team performance on project tasks. Evaluation of instrument performance using aerosols of known size was also done as part of QA system audits conducted to assess the accuracy of particle size measurements. QA for particle concentration measurement was hampered by the lack of a concentration standard, which is a problem common to aerosol science investigations today. Thus, the standard practice in aerosol work is to verify particle concentration by comparing results from two identical condensation particle counters (CPC) and rely on instrument manufacturer calibrations. A fundamental component QA for assessment of instruments and sampling system performance was investigation of particle losses. Along an aerosol sample pathway from source to collection media or measuring instrument, some particles are lost to surfaces. The magnitude of these losses as a function of particle size was determined experimentally by challenging the sampling trains with monodisperse particles in the sub-50 nm aerodynamic diameter size range (nm=10sup -sup 9 meters). Since the most probable loss mechanism was diffusion for sub-50 nm sized particles, theoretical calculations of diffusion loss for 100 nm particles and smaller were also made. Results indicated average sampling train total losses of approximately 50% and 20% for 10 nm and 17 nm size particles, respectively. Measured Scanning Mobility Particle Sizer (SMPS) instrument internal losses were approximately 70% for a 10 nm size mono-disperse aerosol. Measured sample line losses were better predicted by theory if the flow in the sampling lines is considered turbulent. However, the flow in the lines was laminar. This noted discrepancy may be the result of local turbulence created by valves and bends in the sample lines and is an area recommended for additional investigation. Finally, application of a particle loss correction to particle size distributions from the study increased SMPS number concentrations at 10 nm by approximately a factor of 5 and at 20 nm by a factor of 2.

Brundish, K. D.; Hilton, M.; Jefferies, M.; Johnson, M. P.; Miller, M. N.; Wilson, C. W., 2003, "Measurement of smoke particle size and distribution within a gas turbine combustor," *American Society of Mechanical Engineers, International Gas Turbine Institute, Turbo Expo (Publication) IGTI*, **2**:455–462

The objective of the work described in this paper was to identify a method of making measurements of the smoke particle size distribution within the sector of a gas turbine combustor, using a Scanning Mobility Particle Sizing (SMPS) analyser. As well as gaining a better understanding of the combustion process, the principal reasons for gathering these data was so that they could be used as validation for Computational Fluid Dynamic (CFD) and chemical kinetic models. Smoke mass and gaseous emission measurements were also made simultaneously. A "water cooled," gas sampling probe was utilized to perform the measurements at realistic operating conditions within a generic gas turbine combustor sector. Such measurements had not been previously performed and consequently initial work was undertaken to gain confidence in the experimental configuration. During this investigation, a limited amount of data were acquired from three axial planes within the combustor. The total number of test points measured were 45. Plots of the data are presented in 2 dimensional contour format at specific axial locations in addition to axial plots to show trends from the primary zone to the exit of the combustor. Contour plots of smoke particle size show that regions of high smoke number concentration once formed in zones close to the fuel injector persist in a similar spatial location further downstream. Axial trends indicate that the average smoke particle size and number concentration diminishes as a function of distance from the fuel injector. From a technical perspective, the analytical techniques used proved to be robust. As expected, making measurements close to the fuel injector proved to be difficult. This was because the quantity of smoke in the region was greater than 1000 mg/m^3. It was found necessary to dilute the sample prior to the determination of the particle number concentration using SMPS. The issues associated with SMPS dilution are discussed. 10 Refs.

Clark, Nigel N.; Gautam, Mridul; Boyce, James; Xie, Wenwei; Mehta, Sandeep; Jarett, Ron; Rapp, Byron, 2003, “Heavy-duty vehicle exhaust plume study in the NASA/Langley wind tunnel,” *JSAE Technical Paper No. 20030290, 2003 JSAE/SAE International Spring Fuels and Lubricants Meeting*, May 19–22, 2003, Yokohama, Japan

Concern over health effects associated with diesel exhaust and debate over the influence of high number counts of particles in diesel exhaust prompted research to develop a methodology for diesel particulate matter (PM) characterization. As part of this program, a tractor truck with an electronically managed diesel engine and a dynamometer were installed in the Old Dominion University (ODU) Langley full-scale wind tunnel. This arrangement permitted repeat measurements of diesel exhaust under realistic and reproducible conditions and permitted examination of the steady exhaust plume at multiple points. Background particle size distribution was characterized using a Scanning Mobility Particle Sizer (SMPS). In addition, a remote sampling system consisting of a SMPS, PM filter arrangement, and carbon dioxide (CO_2) analyzer, was attached to a roving gantry allowing for exhaust plume sampling in a three-dimensional grid. Raw exhaust CO_2 levels and truck performance data were also measured. The plume centerline was mapped and dilution ratios were determined and mapped. At 55 mph truck wheel speed and steady wind speed operation, at 200 inches behind the stack at the plume centerline, the dilution ratio was about 75, and at 337 inches behind the stack the dilution ratio was about 125. The truck was also operated through repeated transient tests, from 40 to 55 mph, with a wind speed of 47 mph. CO_2 variations in the plume were clearly detected during the transients. Steadystate PM size measurements were made at scan rates of 90 seconds. Ambient samplers located in the tunnel determined PM loading by mass. This paper presents the methodology used, discusses the plume location and dilution, and discusses results from ambient samplers. Particle sizing results are given in a companion paper.

Gautam, Mridul; Clark, Nigel N.; Mehta, Sandeep; Boyce, James A.; Rogers, Fred; Gertler, Alan, 2003, “Concentrations and size distributions of particulate matter emissions from a Class-8 heavy-duty diesel truck tested in a wind tunnel,” *JSAE Technical Paper No. 20030291, 2003 JSAE/SAE International Spring Fuels and Lubricants Meeting*, May 19–22, 2003, Yokohama, Japan

In an effort to develop engine/vehicle test methods that will reflect real-world emission characteristics, West Virginia University (WVU) designed and conducted a study on a Class-8 tractor with an electronically controlled diesel engine that was mounted on a chassis dynamometer in the Old Dominion University Langley full-scale wind tunnel. With wind speeds set at 88 km/hr in the tunnel, and the tractor operating at 88 km/hr on the chassis dynamometer, a Scanning Mobility Particle Sizer (SMPS) was employed for measuring PM size distributions and concentrations. The SMPS was housed in a container that was attached to a three-axis gantry in the wind tunnel. Background PM size-distributions were measured with another SMPS unit that was located upstream of the truck plume. Ambient temperatures were recorded at each of the sampling locations. The truck was also operated through transient tests with vehicle speeds varying from 65 to 88 km/hr, with a wind speed of 76 km/hr. Sampling of the plume, with the truck operating at 88 km/hr revealed unimodal distributions with geometric mean diameter (GMD) values ranging from 55 to 80 nm. When size distributions from five locations in the plume were corrected for concentration with respect to dilution, they were found to be similar. Size distributions and concentrations of PM emissions from the tractor operating at 88 km/hr were found to agree with those from few other heavy-duty diesel vehicles that this team of researchers had previously tested in the field using the WVU Transportable Heavy-duty Vehicle Emissions Testing Laboratory. Under idle operation a distinct nuclei mode was detected with GMD varying from 14 to 24 nm.

Hirabayashi, Motohiro, 2003, “Size distribution of Ultra-Fine Particles in the Roadside Atmospheres,” *JSAE Technical Paper No. 20035679, JSAE Autumn Conference*, September 17–19, 2003, Tokyo, Japan

Size distribution of ultra-fine particle was measured by using the Scanning Mobility Particle Sizer in the roadside of three places with different traffic conditions, in order to grasp the influence of exhaust ultra-fine particles to the atmospheric environment. The high-concentration, ultra-fine particles under the 50 nm diameter that is thought it originates in the vehicle exhaust, was observed in each roadside atmospheres. It was found that the heavy-duty vehicles have contributed largely for the particles under 50 nm diameter, and the contribution of exhaust soot is large for the particles above 50 nm diameter.

Hope A. M., 2003, “Development of detection techniques and diagnostics for airborne carbon nanoparticles,” *Technical Report*, Sandia National Laboratories, Albuquerque, NM; Livermore, CA, US, Report No. 2003–8666

We have recorded time-resolved LII signals from a laminar ethylene diffusion flame over a wide range of laser fluences at 532 nm. We have performed these experiments using an injection-seeded Nd:YAG laser with a pulse duration of 7 ns. The beam was spatially filtered and imaged into the flame to provide a homogeneous spatial profile. These data were used to aid in the development of a model, which will be used to test the validity of the LII technique under varying environmental conditions. The new model describes the heating of soot particles during the laser pulse and the subsequent cooling of the particles by radiative emission, sublimation, and conduction. The model additionally includes particle heating by oxidation, accounts for the likelihood of particle annealing, and incorporates a mechanism for nonthermal photodesorption, which is required for good agreement with our experimental results. In order to investigate the fast photodesorption mechanism in more detail, we have recorded LII temporal profiles using a regeneratively amplified Nd:YAG laser with a pulse duration of 70 ps to heat the particles and a streak camera with a temporal resolution ofapprox65 ps to collect the signal. Preliminary results confirm earlier indications of a fast mechanism leading to signal decay rates of much less than a nanosecond. Parameters to which the model is sensitive include the initial soot temperature, the temperature of the ambient gas, and the partial pressure of oxygen. In order to narrow the model uncertainties, we have developed a source of soot that allows us to determine and control these parameters. Soot produced by a burner is extracted, diluted, and cooled in a flow tube, which is equipped with a Scanning Mobility Particle Sizer (SMPS) for characterization of the aggregates.

Johnson, M. P.; Hilton, M.; Waterman, D. R.; Black, J. D., 2003, “Development of techniques to characterize particulates emitted from gas turbine exhausts,” *Measurement Science and Technology*, **14**

Particles emitted from aircraft play a role in the formation of contrails and it is essential to characterize them to understand the physical and chemical processes that are happening. Current methods for measuring aircraft particulate emissions study the reflectance of samples collected in filter papers. A series of experiments to more fully characterize particulates has been performed on a small-scale gas turbine engine. An intrusive sampling system conforming to current ICAO regulations for aircraft emissions was used with a scanning mobility particle sizer (SMPS). Non-intrusive measurements were made using laser induced incandescence (LII) and samples were taken from the exhaust to analyze using a transmission electron microscope. Results obtained from different techniques showed good agreement with each other. As engine power conditions increased, both the SMPS and LII indicated that the mass of soot had decreased. Differences were observed between measurements of diluted and undiluted samples. The mean particle size decreased with dilution but the size distribution became bi-modal. The study has shown how significant the sampling environment is for measuring particulates and careful techniques need to be used to ensure that accurate, consistent results can be obtained.

Johnson, T; Caldow, R; Pucher, A; Mirme, A; Kittelson, D, 2003, "An Engine Exhaust Particle Sizer^{TM} spectrometer for transient emission particle measurements," *9th Diesel Engine Emissions Reduction (DEER) Workshop 2003*, Newport, RI (US), 08/24/2003–08/28/2003

There has been increased interest in obtaining size distribution data during transient engine operation where both particle size and total number concentrations can change dramatically. Traditionally, the measurement of particle emissions from vehicles has been a compromise based on choosing between the conflicting needs of high time resolution or high particle size resolution for a particular measurement. Currently the most common technique for measuring submicrometer particle sizes is the Scanning Mobility Particle Sizer^{TM} (SMPS^{TM}) system. The SMPS system gives high size resolution but requires an aerosol to be stable over a long time period to make a particle size distribution measurement. A Condensation Particle Counter (CPC) is commonly used for fast time response measurements but is limited to measuring total concentration only. This paper describes a new instrument, the Engine Exhaust Particle Sizer^{TM} (EEPS^{TM}) spectrometer, which has high time resolution and a reasonable size resolution. The EEPS was designed specifically for measuring engine exhaust and, like the SMPS system, uses a measurement based on electrical mobility. Particles entering the instrument are charged to a predictable level, then passed through an annular space where they are repelled outward by the voltage from a central column. When the particles reach electrodes on the outer cylindrical (a column of rings), they create a current that is measured by an electrometer on one or more of the rings. The electrometer currents are measured multiple times per second to give high time resolution. A sophisticated real-time inversion algorithm converts the currents to particle size and concentration for immediate display.

Khalek, Imad A.; Fritz, Steven G.; Paas, Norbert, 2003, "Particle size distribution and mass emissions from a mining diesel engine equipped with a dry system technologies emission control system," *JSAE Technical Paper No. 20030244, 2003 JSAE/SAE International Spring Fuels and Lubricants Meeting*, May 19–22, 2003, Yokohama, Japan

Particle size distribution, number, and mass emissions from the exhaust of a 92 kW 1999 Isuzu 6BG1 non-road naturally aspirated diesel engine were measured. The engine exhaust was equipped with a Dry System Technologies(R) (DST) auxiliary emission control device that included an oxidation catalyst, a heat exchanger, and a disposable paper particulate filter. Particle measurement was taken during the ISO 8178 8-mode test for engine out and engine with the DST using a scanning mobility particle sizer (SMPS) in parallel to the standard filter method (SFM), specified in 40 CFR, Part 89. The DST efficiency of removing particles was about 99.9 percent based on particle number, 99.99 percent based on particle mass derived from number and size. However, the efficiency based on mass derived from the SFM was much lower on the order of 90 to 93 percent. This discrepancy in particle mass efficiency between the two methods was mainly due to poor correlation between the mass derived from number and size and the mass measured using the SFM. This poor correlation was obtained for the DST out particulate matter (PM) emission and not for engine out. For DST out PM, the SFM tends to exaggerate the mass emissions of particles due to the condensation/adsorption of gas phase non-aerosol volatile compounds on the Palflex T60A20 filters used for particle mass measurement, thus resulting in a lower efficiency of particle removal. If the health effect of particles is due to the mass and number of their physical characteristics, particle measurement using the SFM may need rethinking, particularly if the nature of the measured product is dominated by volatile rather than soot.

Khalek, Imad A.; Spears, Matt; Charmley, William, 2003, "Particle size distribution from a heavy-duty diesel engine: Steady-state and transient emission measurement using two dilution systems and two fuels," *SAE 2003 World Congress*, March 3–6, 2003, Detroit, Michigan, USA

Particle size distribution and number concentration were measured in the dilute exhaust of a heavy-duty diesel engine for steady-state and transient engine operation using two different dilution systems that included a full flow CVS that was coupled to an ejector pump (CVS-EP), and a double- ejector, micro-dilution tunnel (DEMDT) that was connected to engine exhaust close to turbocharger outlet. Measurements were performed using a scanning mobility particle sizer (SMPS), an electrical low-pressure impactor (ELPI), and a parallel flow diffusion battery (PFDB). Fuels with sulfur content of about 385 ppm and 1 ppm were used for this work. The PFDB performed well in measuring nanoparticles in the size range below 56 nm when compared with the SMPS. This was especially valid when a distinct log-normal size distribution in the size range below 56 nm in diameter, the upper size limit of the PFDB, was present. The dilution method and the sulfur content in the fuel influenced the characteristics of the size distributions significantly under both steady-state and the FTP hot-start transient cycle. The CVS-EP resulted in more particle growth and higher number of nanoparticles compared to the DEMDT. Harmonizing the measurement method of total particle number and size emissions from engines by providing a reference condition to variables such as dilution temperature, dilution rate, dilution ratio, relative humidity, dilution and transfer line residence time, will be a key next step in developing a protocol and a standard operating procedure for such measurement. Until then, different researchers will continue to produce different results in measuring total particle size and number, depending on the sampling and dilution system selected.

Kweon, Chol-Bum; Okada, Shusuke; Stetter, John C.; Christenson, Charles G.; Shafer, Martin M.; Schauer, James J.; Foster, David E., 2003, "Effect of fuel composition on combustion and detailed chemical/physical characteristics of diesel exhaust," *JSAE Technical Paper No. 20030098, 2003 JSAE/SAE International Spring Fuels and Lubricants Meeting*, May 19–22, 2003, Yokohama, Japan

An experimental study was performed to investigate the effect of fuel composition on combustion, gaseous emissions, and detailed chemical composition and size distributions of diesel particulate matter (PM) in a modern heavy-duty diesel engine with the use of the enhanced full dilution tunnel system of the Engine Research Center (ERC) of the UW Madison. Detailed description of this system can be found in our previous reports. The experiments were carried out on a single-cylinder, 2.3-liter D.I. diesel engine equipped with an electronically controlled unit injection system. The operating conditions of the engine followed the California Air Resources Board (CARB) 8-mode test cycle. The fuels used in the current study include baseline No. 2 diesel (Fuel A: sulfur content = 352 ppm), ultra-low-sulfur diesel (Fuel B: sulfur content = 14 ppm), and Fisher Tropsch (F-T) diesel (sulfur content = 0 ppm). Samples were collected on a series of Teflon and baked quartz fiber filters to evaluate mass loading, elemental and organic carbon (EC/OC), sulfates (SOsub 4sup 2sup -), and trace metals for the three different fuel compositions. A scanning mobility particle sizer (SMPS) was used to measure particle number concentrations and size distributions. Results show that the fuel composition significantly affected combustion, mass loading, chemical composition, and number concentrations and size distributions of PM. Mass loading, EC, and sulfates were significantly lowered with the advanced diesel fuels (Fuel B and F-T fuel) at higher loads. The advanced diesel fuels also produced more nucleimode particles and less accumulation-mode particles than Fuel A at high load conditions. In contrast, the former produced less nuclei-mode particles and more accumulation mode particles than the latter at the medium load conditions.

Kweon, Chol-Bum; Okada, Susuke; Stetter, John C.; Christenson, Charles G.; Shafer, Martin M.; Schauer, James J.; Foster, David E., 2003, “Effect of injection timing on detailed chemical composition and particulate size distributions of diesel exhaust,” *JSAE Technical Paper No. 20030099, 2003 JSAE/SAE International Spring Fuels and Lubricants Meeting*, May 19–22, 2003, Yokohama, Japan

An experimental study was carried out to investigate the effects of fuel injection timing on detailed chemical composition and size distributions of diesel particulate matter (PM) and regulated gaseous emissions in a modern heavy-duty D.I. diesel engine. These measurements were made for two different diesel fuels: No. 2 diesel (Fuel A) and ultralow-sulfur diesel (Fuel B). A single-cylinder, 2.3-liter D.I. diesel engine equipped with an electronically controlled unit injection system was used in the experiments. PM measurements were made with an enhanced full-dilution tunnel system at the Engine Research Center (ERC) of the University of Wisconsin-Madison (UW Madison). The engine was run under 2 selected modes (25% and 75% loads at 1200 rpm) of the California Air Resources Board (CARB) 8-mode test cycle. Samples were collected on a series of Teflon and baked quartz fiber filters to evaluate mass loading, elemental and organic carbon (EC/OC), and sulfates (SOsub 4sup 2sup -) for several injection timings with the two different fuel compositions. A scanning mobility particle sizer (SMPS) was used to measure particle number concentrations and size distributions in the residence time chamber (RTC). Results show that the advanced injection timing significantly affected detailed chemical composition and size distributions of the PM. The advanced injection timing significantly decreased EC and modestly decreased OC, particularly at the higher load (mode 6). The impact on OC with changing fuel composition and the fuel composition's effect on changes in OC with injection timing were negligible and statistically insignificant. Sulfates did not change with the injection timing and/or engine load for Fuel B, however, Fuel A showed significant variations in the sulfates with the injection timing and/or engine load.

Lapuerta, M; Armas, O; Gomez, A, 2003, “Diesel particle size distribution estimation from digital image analysis,” *Aerosol Science and Technology*, **37**:369–381

One of the most serious problems associated with Diesel engines is pollutant emissions, especially nitrogen oxides and particulate matter. However, although current emissions standards in Europe and America with regard to light vehicles and heavy duty engines refer to the particulate limit in mass units, there has been increasing concern of late to know the size and number of particles emitted by engines. This interest has been promoted by the latest studies about the harmful effects of particles on health and is enhanced by recent changes in internal combustion engine technology. This study is focused on the implementation of a method to determine the particle size distribution that could be appropriate for the current methodology of vehicle certification in Europe. This method uses an automated Digital Image Analysis Algorithm (DIAA) to determine particle size trends from Scanning Electron Microscope (SEM) images of filters charged in a partial dilution system used for measuring specific particulate emissions. The experimental work was performed on a stationary electric generation direct injection Diesel engine with 0.5 MW (671 hp) rated power, which is considered as a typical engine in middle power industries. Particulate size distributions obtained using DIAA were compared with distributions obtained using an Optical Particle Counter (OC) and a Scanning Mobility Particle Sizer (SMPS), the latter currently considered as the most reliable technique. Although the number concentration detected by this method does not represent the real flowing particle concentration, the algorithm gives a fair reproduction of the trends observed with on-line techniques (SMPS and OC) when the engine load is varied.

Lehmann, U.; Mohr, M.; Schweizer, T.; Ruetter, J., 2003, “Number size distribution of particulate emissions of heavy-duty engines in real world test,” *Atmospheric Environment*, **37**(37):5247–5259

Five in-service engines in heavy-duty trucks complying with Euro II emission standards were measured on a dynamic engine test bench at EMPA. The particulate matter (PM) emissions of these engines were investigated by number and mass measurements. The mass of the total PM was evaluated using the standard gravimetric measurement method, the total number concentration and the number size distribution were measured by a Condensation Particle Counter (lower particle size cut-off: 7 nm) and an Electrical Low Pressure Impactor (lower particle size: 32 nm), respectively. The transient test cycles used represent either driving behaviour on the road (real-world test cycles) or a type approval procedure. They are characterized by the cycle power, the average cycle power and by a parameter for the cycle dynamics. In addition, the particle number size distribution was determined at two steady-state operating modes of the engine using a Scanning Mobility Particle sizer. For quality control, each measurement was repeated at least three times under controlled conditions. It was found that the number size distributions as well as the total number concentration of emitted particles could be measured with a good repeatability. Total number concentration was between 9x10 and $1x10^{13}$ particles/s ($3x10^{13}$ -$7x10^{14}$ p/kWh) and mass concentration was between 0.09 and 0.48 g/kWh. For all transient cycles, the number mean diameter of the distributions lay typically at about 120 nm for aerodynamic particle diameter and did not vary significantly. In general, the various particle measurement devices used reveal the same trends in particle emissions. We looked at the correlation between specific gravimetric mass emission (PM) and total particle number concentration. The correlation tends to be influenced more by the different engines than by the test cycles.

Maguhn, J.; Karg, E.; Kettrup, A.; Zimmermann, R., 2003, “On-line Analysis of the Size Distribution of Fine and Ultrafine Aerosol Particles in Flue and Stack Gas of a Municipal Waste Incineration Plant: Effects of Dynamic Process Control Measures and Emission Reduction Devices,” *Environmental Science & Technology*, **37**(20):4761–4770

The size distribution of particles in the waste gas of a municipal waste incineration plant (23 MW) was measured on-line at two sampling points in the flue-gas duct (700 and 300 degree C) as well as in the stack gas (80 degree C). The measurements were performed during both stable combustion conditions and transient operating conditions. The particle measurements were carried out by a mobile system consisting of a home-designed sampling system with dilution device and a scanning mobility particle sizer (SMPS) for the particle size range 17-600 nm as well as an aerodynamic particle sizer (APS) for the size range 500 nm-30 µ m. The

APS and SMPS data were combined using a special method and a home written software tool. The maximum of the particle-size distribution in the flue gas of the incinerator shifts from about 90 nm at the 700 degree C sampling point to about 140 nm at the 300 degree C point, showing the particle growth by coagulation processes and condensation of inorganic and organic gaseous species with decreasing temperature. This finding is consistent with the measured concentration profiles of gaseous organic chemical species in the flue gas. While at flue-gas temperatures of 600-800 degree C a rich pattern of polycyclic aromatic hydrocarbon species (PAH) is observable, the PAH concentrations are considerably reduced further downstream of the flue-gas channel, where the temperature drops below 500 degree C. Condensation and reactive bonding of gaseous chemicals onto particulate matter is, among other reasons, responsible for the depletion of gas-phase species. Process control measures, such as firing the backup burners or cleaning of the grate with pressurized air, can cause dynamic changes of the particle-size distribution. Furthermore the flue-gas cleaning measures have great impact onto both the particle concentration and the size distribution. For this reason the impact of one particular emission reduction device, the wet electrostatic dust precipitator (wet-ESP), is evaluated. The wet-ESP reduces considerably the particle concentration over the whole size range. Behind the flue-gas processing units a broad maximum in the particle-size distribution occurs at about 70 nm, but no pronounced particle-size distribution could be observed. The particle concentration level at this maximum is about 3 magnitudes lower than in the raw flue gas. However, intermittent periods lasting for several minutes of high emissions of ultrafine particles with d < 40 nm were observed. These particles are most likely formed by nucleation processes behind the wet-ESP from gas-phase constituents of the stack gas.

McMurry, P. H.; Cao, F.; Kittelson, D. B.; Park, K., 2003, “Relationship between particle mass and mobility for diesel exhaust particles,” *Environmental Science & Technology*, **37**(3):577–583

We used the aerosol particle mass analyzer (APM) to measure the mass of mobility-classified diesel exhaust particles. This information enabled us to determine the effective density and fractal dimension of diesel particles as a function of engine load. We found that the effective density decreases as particle size increases. TEM images showed that this occurs because particles become more highly agglomerated as size increases. Effective density and fractal dimension increased somewhat as engine load decreased. TEM images suggest that this occurs because these particles contain more condensed fuel and/ or lubricating oil. Also, we observed higher effective densities when high-sulfur EPA fuel (apprx360 ppm S) was used than for Fischer-Tropsch fuel (apprx0 ppm S). In addition, the effective density provides the relationship between mobility and aerodynamic equivalent diameters. The relationship between these diameters enables us to intercompare, in terms of a common measure of size, mass distributions measured with the scanning mobility particle sizer (SMPS) and a MOUDI impactor without making any assumptions about particle shape or density. We show that mass distributions of diesel particles measured with the SMPS-APM are in good agreement with distributions measured with a MOUDI and a nano-MOUDI for particles larger than apprx60 nm. However, significantly more mass and greater variation were observed by the nano-MOUDI for particles smaller than 40 nm than by the SMPS-APM.

Okada, Shusuke; Kweon, Chol-Bum; Stetter, John C.; Foster, David E.; Shafer, Martin M.; Christensen, Charles G.; Schauer, James J.; Schmidt, Alexandra M.; Silverberg, Amy M.; Gross, Deborah S., 2003, “Measurement of trace metal composition in diesel engine particulate and its potential for determining oil consumption: ICPMS (inductively coupled plasma mass spectrometer) and ATOFMS (aerosol time of flight mass spectrometer) measurements,” *SAE 2003 World Congress*, March 3–6, 2003, Detroit, Michigan, USA

Current regulations stipulate acceptable levels of particulate emissions based on the mass collected on filters obtained by sampling in diluted exhaust. Although precise, this gives us only aggregated information. If in addition to the mass-based measurements, detailed chemical analysis of the particulate matter (PM) is performed, additional subtle information about the combustion process can be revealed. This paper reports the results of detailed chemical analysis of trace metal in the PM emitted from a single-cylinder, heavy-duty diesel engine. The trace metal concentrations are used as an indicator of oil consumption. Two techniques were used to make the trace metal concentration measurements. PM was captured on filters and trace metals were quantified with an Inductively Coupled Plasma Mass Spectrometer (ICPMS), and also an Aerosol Time- of-Flight Mass Spectrometer (ATOFMS) was used to perform particle size and composition measurements in real time. Particle size distributions were also measured using a Scanning Mobility Particle Sizer (SMPS). Aerosol Time-of-Flight Mass Spectrometers have been widely used to study atmospheric aerosols, but only limited ATOFMS measurements have been collected for internal combustion engine exhaust emissions. The instrument yields data of a single particle size and composition for a particle size range from 0.2 to 3 micrometers. Mass spectral composition analyses are completed at a rate of up to t~200 particles per minute. In this work we compare trace metals, elemental carbon (EC) and organic carbon (OC) concentrations from the ATOFMS with more traditional filter- based and particle size distribution data to assess the utility of using ATOFMS for real-time fundamental engine exhaust studies. The data presented covers the operating modes of California Air Resources Board (CARB 8 mode) emissions test. Dramatic changes in trace metals, EC and OC, and PM size with changes in the engine operating modes are evident from both filters and ATOFMS, which illustrates that the chemical and physical characteristics of the PM, especially trace metals, EC and OC concentrations, are highly dependant on the engine operating conditions. The results show chemical compositions of each particle and the contribution of the lubricating oil to the PM.

Wong, C. P.; Chan, T. L.; Leung, C. W., 2003, “Characterisation of diesel exhaust particle number and size distributions using mini-dilution tunnel and ejector-diluter measurement techniques,” *Atmospheric Environment*, **37**(31):4435–4446

This paper presents the characteristics of diesel exhaust particle number and size distributions. These were measured for different engine load conditions from 10% to 100% of full engine load at a maximum torque of constant speed, using mini-dilution tunnel and sampling (MDTS) and ejector-diluter and sampling (EDS) systems. The exhaust particles sampled were analyzed using a scanning mobility particle sizer (SMPS). In general, the particle number concentration increased with increasing engine load using both measurement systems. Comparing the particle number and volume concentrations, the MDTS system measures a lower level in the nanoparticle range, $D_p<50$ nm, but a higher level in the accumulation mode size range, $50<D_p670$ nm, than the EDS system. The measurements also showed that the MDTS system shifted the particle count median diameter (CMD) to larger particle diameter and the particle number size and volume distribution for all engine load conditions. It is mainly because the mini-dilution tunnel leads to the particle transformations of nucleation and condensation taking place simultaneously when the exhaust particle emissions are cooled and diluted. However, the effect of coagulation on the total number particle concentration was shown to be negligible. On the other hand, the EDS measurement system can minimize the particle transformations taking place on the exhaust particle number and size distributions during the heated dilution process. Hence, the EDS measurement system can provide more reliable diesel exhaust particle number and size distributions than MDTS measurement system.

Zhao, B.; Yang, Z.; Johnston, M. V.; Wang, H.; Wexler, A. S.; Balthasar, M.; Kraft, M., 2003, “Measurement and numerical simulation of soot particle size distribution functions in a laminar premixed ethyleneoxygen-argon flame,” *Combustion and Flame*, **133**(1–2):173–188

Spatially resolved measurement of the soot particle size distribution function (PSDF) was made in a laminar premixed ethylene-argon-oxygen flame (phi = 2.07) using a scanning mobility particle sizer. The emphasis of the study was to follow the evolution of the PSDF from the onset of particle inception to particle mass growth. At the onset of soot inception, the PSDF was found to follow a power-law dependence on particle diameter. The PSDF becomes bimodal at larger height above the burner surface, and remains bimodal throughout the flame. Numerical simulation using a kinetic model proposed previously and a stochastic approach to solve aerosol dynamics equations again showed a bimodal PSDF. Further analysis revealed that bimodality is intrinsic to an aerosol process involving particle-particle coagulation and particle nucleation dominated by monomer dimerization.

Zhao, B.; Yang, Z.; Wang, J.; Johnston, M. V.; Wang, H, 2003, “Analysis of Soot Nanoparticles in a Laminar Premixed Ethylene Flame by Scanning Mobility Particle Sizer,” *Aerosol Science and Technology*, **37**(8): 611–620

Mobility size distributions of soot particles produced from a fuel-rich, laminar premixed ethylene flat flame were obtained by in situ probe sampling and online analysis using a nano scanning mobility particle sizer. The emphasis of the work was the development of an in situ sampling technique to follow the evolution of nanoparticles formed in flames. Particle size distribution functions were obtained along the centerline of the flame in a spatially resolved manner. Considerable efforts were made to eliminate particle losses in the sample probe. To this end, the effect of dilution on particle losses in the sample probe was systematically studied. It is demonstrated that particle losses due to coagulation and diffusive wall deposition were negligible using a dilution ratio greater than ~104. The sampling technique is shown to be capable of closely following the evolution of particle size distribution from the nucleation mode to mass growth mode dominated by particle coagulation and gas-surface reactions. Beyond the particle nucleation region of the flame, the size spectra were found to be distinctively bimodal, indicating sustained particle nucleation throughout the flame studied.

2002

Blevins, L. G.; Cauley III, T. H., 2002, “Fine particulate formation during biomass/coal cofiring,” *ASME Heat Transfer Div Publ HTD*, **372**(3):295–299

Experiments to examine the effects of biomass/coal cofiring on fine particle formation were performed in the Sandia Multi-Fuel Combustor using fuels of pure coal, 3 combinations of switchgrass and coal, and pure switchgrass. A constant thermal input was maintained. The combustion products were cooled during passage through the 4.2 m long reactor to simulate the temperatures experienced in the convection pass of a boiler. Fine particle number densities, mass concentrations, and total number concentrations for particles between 10 nm and 1 µm at the reactor exit were determined using a Scanning Mobility Particle Sizer. The results indicate that the fine particle loading for cofiring is higher than that achieved with dedicated coal combustion but lower than that achieved with dedicated switchgrass combustion. 9 Refs.

Fogh, C.; Jensen, J. N.; Livbjerg, H.; Lund, C.; Nielsen, M. T.; Poulsen, K.; Sander, B.; Simonsen, P., 2002, “Formation and emission of fine particles from two coal-fired power plants,” *Combustion Science and Technology*, **174**(2):79–113

A field study of the formation and emission of fine particles from two Danish full-scale, coal-fired power plants at Avedriv similar to Qrket and Nordjyllandsv similar to Qrket was performed using a so-called multi-platform approach. The measurements were made simultaneously at three positions in the plants: platform 1 at the inlet to the electrostatic precipitator, platform 2 at the outlet of the electrostatic precipitator, and platform 3 in the stack. The combined data from the three measuring platforms provide information about all key particle processes in the plant, such as the generation of particles in the boiler, the ESP filtering efficiency, the influence of the flue gas desulfurization plant, and the emissions from the stack. 23 Refs.

Franke, H. U., 2002, “Exhaust gas concept for EURO 4 passenger car diesel engine. Subproject: Various measurements and analyses of particle emissions, carried out on the 1.9 l PDE engine equipped with diesel particle filter,” Report, Magdeburg Univ.

A complex research, leading to accomplishment of EURO 4 exhaust limits, should be examined in the case of a Diesel engine, equipped with a direct injection PDE system. Tests have been done on the stationary test bench, as well as on two passenger cars driven on the chassis dynamometer. Diesel fuel with a sulphur content of 45 ppm has been used. To decrease the soot ignition temperature, different additives have been employed. An oxidation catalyst with DeNO{sub x} effect found a place in front of the Diesel particle filter (DPF). The data of particle mass, particle size distribution particle number as well as morphological structure of particles and agglomerates have been examined by the use of a Berner low pressure impactor, a Scanning Moblity Particle Sizer (SMPS) and a morphological measurement system. Generally, the particle emission reduction has been observed at all engine loads with every further modification of an engine control unit, when DPF designed by HJS company was applied. The efficiency of HJS DPF no. 1 was 98,1% by 25% load, 97,9% by 50% load and 87,9% by 75% engine load. A similar conclusion can be also done for the HJS DPF no. 2. The morphological research results are more or less similar for both HJS DPF versions. The mean agglomerate diameter is about 600 nm in front of DPF. However, there are less single particles but many drops with and without solid nuclei behind DPF. Single particles then usually have size of 8 nm, drops about 50 nm. The highest particle filter efficiency of DPF designed by OM company (version no. 1) has been found in the case of the test car VP 91, particularly by 25% engine load. The efficiency rate was 74,6%. Due to a very high soot concentration, caused by an ECU modification, it was not possible to carry out the same measurements on the stationary engine test bench. In the case of OM DPF no. 2, tests on the stationary test bench have shown that the particle filter efficiency is approximately 45%. Besides, the results show that DPF regeneration requires an improvement of exhaust gas temperature, especially within an idle operation mode. Unfortunately, available hardware and software equipment was not enough to reach this higher temperature level at every operation mode of tested PDE Diesel engine.

Jeuland, N.; Dementhon, J. B.; Plassat, G.; Coroller, P.; Momique, J. C.; Belot, G.; Bruchet, D., 2002, "Performances and durability of DPF (diesel particulate filter) tested on a fleet of Peugeot 607 Taxis - First and second test phases results," *Powertrain and Fluid Systems Conference and Exhibition*, October 21–24, 2002, San Diego, California, USA

The use of diesel engines has strongly increased during the last years and now represents 30% of the sales in Europe and up to 50% of the number of cars in circulation for some countries. This success is linked not only to the economical aspect of the use of such vehicles, but also to the recent technological improvements of these engines. The new technical solutions (high pressure direct injection, turbocharging ...) have indeed allowed the increase of these engine performances while decreasing their fuel consumption, pollutant emissions and noise level. From an environmental point of view, diesel engines are nevertheless penalized by their particulate and NOx emissions. The study and the treatment of the particulate, highly criticized for their potential impact on health, are the subject of numerous works of characterization and developments. PSA Peugeot-Citroen has recently launched its particulate filter technology on several types of vehicles. In order to evaluate the durability of this technology over a long period of time, a study program has been set-up by ADEME (French environmental agency), IFP Powertrain, PSA Peugeot-Citroen and G7 (a Parisian taxi company). The objective is to study the evolution of several taxis and their after-treatment system performances over 80,000 km mileage in hard urban driving conditions, which corresponds to the recommended mileage before the first DPF maintenance. More specifically, the following evaluations are being performed at regular intervals (around 20,000 km): - Regulated gaseous pollutant emissions on NEDC cycle (New European Driving Cycle); - Particulate emissions, by mass measurement on NEDC but also by particle number and size measurement with SMPS (Scanning Mobility Particle Sizer) technique on NEDC and on unconventional steady-state running points; - Unregulated pollutant emissions (hydrocarbons speciation C_1-C_{13}, oxygenated compounds). The results obtained until now have not shown any degradation of the particulate filter efficiency. This paper presents the methodology setup and the explanation of the first results obtained. Indeed, a more specific study has shown that most of the aerosols measured with SMPS are composed of liquid fractions, mainly sulfates due to sulfur coming from the fuel, but also from the lubricant. The impact of sulfates stored on the catalyst surface during low-temperature running phases and removed during high- temperature running phases has also been outlined.

Kweon, Chol-Bum; Foster, David E.; Schauer, James J.; Okada, Shusuke, 2002, "Detailed chemical composition and particle size assessment of diesel engine exhaust," *Powertrain and Fluid Systems Conference and Exhibition*, October 21–24, 2002, San Diego, California, USA

A dilution source sampling system has been incorporated into the exhaust measurement system of a research single- cylinder diesel engine. To allow more detailed assessment of the individual chemical components of the diesel particulate matter (PM) the exhaust dilution system includes a residence time chamber (RTC) to allow for residence times of 30 to 60 seconds in the second stage of dilution before sampling. Samples are collected on a range of different filters where mass loading, elemental and organic carbon (ECOC), trace metals, sulfate ions (SO_4), particle-phase organic compounds, and semi-volatile organic compounds are evaluated. In addition, particle size distributions have been determined using a scanning mobility particle sizer (SMPS). Results show that the chemical composition of the particulate matter is highly dependent on the engine operating conditions. There is a dramatic shift in the ratio of elemental carbon to organic compounds and in the sulfate ions (SO_4) and trace metals when the engine is traversed across a load and speed range. Similarly there is a shift in the particle size range for which there is virtually no impact on the mass loading.

Sasaki, Sousuke; Nakajima, Toru, 2002, "Study on the measuring method of vehicular PM size distribution to simulate the atmospheric dilution process," Powertrain and Fluid Systems Conference and Exhibition, October 21–24, 2002, San Diego, California, USA

The measuring method of vehicular particulate matter (PM) size distribution to simulate the atmospheric dilution process was studied. PM size distribution was measured with a scanning mobility particle sizer (SMPS). To simulate the atmospheric dilution process with a chassis dynamometer test, a chasing experiment was done in order to obtain reference data. A light-duty diesel truck was selected as a basic test vehicle. Three sizes of prototype partial flow diluters (PPFD) were made to reproduce the PM size in the atmosphere. The PM sizes of the chasing experiment and the PPFD experiment was roughly agreed. Differences in the data obtained from a full flow dilution tunnel and the chasing experiments were investigated. The length of the transfer tube greatly affected the smaller side of the PM number concentration

Zellbeck, H.; Friedrich, J.; Starosta, H.; Schulze, T.; Blei, S.; Liebsch, S.; Reuss, H.C.; Kaemmer, A.; Deutschmann, R., "Methods and tools for system optimization of combustion engines at Dresden University of Technology" *Emission control 2002*. Proceedings, Dresden (Germany), June 10–11, 2002

Reducing fuel consumption and exhaust gas emission of internal combustion engines at Dresden University of Technology computer simulation, experimental tests and hardware in the loop simulations (HiL) are developed and used. Based on MATLAB/SIMULINK mean value models were made for optimizing system performance of super charged combustion engines as well as injection systems. A HiL-Simulation is shown, to influence Sauter mean diameter by a directly actuated piezo Diesel injector in which the fuel is injected through 2 rows of different sized nozzle holes. Also tests of electronic engine control systems are done by HiL-simulation. Optimizing combustion development process a measurement system was developed supported by the FVV to detect liquid Diesel fuel wetting the piston bowl. With the presented scanning mobility particle sizer the particle size distribution of row emission and after filter was measured. The filter efficiency was over 99.9%. On a high dynamic engine test bench the real vehicle driving on the road is simulated (HiL) measuring exhaust gas emission by a fast exhaust gas analyzer. During an acceleration mode peaks of HC and NO-emission as well as smoke emission were detected.

2001

Abu-Qudais, M.; Kittelson, D.; Matson, A., 2001, “Combination of methods for characterization diesel engine exhaust particulate emissions,” *JSME International Journal, Series B: Fluids and Thermal Engineering*, **44**(1):166–170

This paper describes a study of the exhaust aerosols produced by a diesel engine. A combination of techniques for collecting and measure particulate matter in a diluted exhaust gases are presented. Three techniques have been used: a Micro Orifice Uniform Deposit Impactor (MOUDI), a Low Pressure Impactor (LPI) and a Scanning Mobility Particle Sizer (SMPS). A direct injection naturally aspirated diesel engine was used in the study at three different equivalence ratios: 0.3, 0.45, and 0.6 at an engine speed of 1 400 rpm which is rated torque speed. Mass concentration measurements made with the MOUDI were in qualitative, but not quantitative, agreement with those calculated from the aerosol volume concentrations measured by the SMPS. The particulate matter obtained from the LPI was analyzed using transmission electron microscope and was found to be comprised of individual spherical particles ranging from 10 nm to 50,nm with a mean size of approximately 25 nm. Some conclusions about the size distribution measurement possibilities can be drawn. 4 Refs.

Armas, O.; Ballesteros, R.; Gomez, A., 2001, “Morphological Analysis of Particulate Matter Emitted by a Diesel Engine using Digital Image Analysis Algorithms and Scanning Mobility Particle Sizer,” *SAE SP, Diesel emission control systems*, **1641**:31–38

This paper shows the morphological analysis results of particulate matter emissions from an indirect injection diesel engine working in two operating modes using Digital Image Analysis Algorithms (DIAA) and a Scanning Mobility Particle Sizer (SMPS). Two typical engine operating modes were selected among the collection of steady stages, which reproduce the sequence of operating conditions that the vehicles equipped with this type of engines must follow during the transient cycle established in the European Emission Directive 70/220. The DIAA results were obtained from images of particulate matter collected in filters. The filters were charged in a dilution mini-tunnel, connected up-stream and down-stream of a cyclone-based particulate filtration system, which was coupled to the engine exhaust line. The images were obtained by a Scanning Electron Microscope (SEM) from samples taken directly from the charged filters. All the obtained results were compared with the SMPS measurements at the same operating condition and the same sampling points.

Jamriska, M.; Morawska, L., 2001, “A model for determination of motor vehicle emission factors from on-road measurements with a focus on submicrometer particles,” *Science of the Total Environment*, **264**(3):241–255

The multiplicity of parameters that influence traffic-related emissions and that are often very difficult to measure or predict, makes the assessment of traffic emissions a very complicated process, strongly dependent on local conditions and usually associated with a high degree of error. The aim of this paper was to develop, calibrate and test a simple model for 'on-road' measurements of traffic emission factors as part of a major program focused on the assessment of traffic contribution to fine and ultrafine emissions to the whole air shed and to local areas in south-east Queensland, Australia. A mathematical model developed was based on the mass balance concept for on-road assessment of traffic-related emission rates. The model requires fewer experimental data points as input and is more applicable to the common on-road testing situation, when no more than two monitors of a specific pollutant can be used. The model was tested and calibrated using experimental data on particle number concentration collected at a road-monitoring site using the Scanning Mobility Particle Sizer, and was applied to assess the emission factors of submicrometer particles emitted by traffic. The average emission factor obtained using the box model and the experimental data from road measurements was 1.75 x 10^{14} particles km^{-1} $vehicle^{-1}$, with a standard error of 67.6%. While the emission factor obtained was comparable with some results obtained from dynamometer studies and applied to the vehicle mix at the sampling site, they were significantly higher than the factors reported by other studies.

Kim, W.-S.; Kim, S. H.; Lee, D. W.; Lee, S.; Lim, C. S.; Ryu, J. H., 2001, “Size Analysis of Automobile Soot Particles Using Field-Flow Fractionation,” *Environmental Science & Technology*, **35**(6):1005–1012

Soot particles emitted from various automobile engines are analyzed for size distributions using field-flow fractionation (FFF). Soot samples are prepared for FFF analysis using a three-step procedure, where a layer of soot particles is focused between the layers of n-hexane and water, followed by dispersing of particles in water containing 0.05% Triton X-100. The mean diameters determined by FFF show similar trends with those obtained from dynamic light scattering (DLS) and scanning electron microscopy (SEM). Data from FFF are also compared with those from an on-line Scanning Mobility Particle Sizer (SMPS). SMPS size distributions extend further to larger size than those of FFF distributions, which indicates the three-step sample preparation procedure effectively disaggregates the agglomerated particles. Although the amount of particulate matter (PM) emitted from a heavy-duty diesel engine is much higher than that from a light-duty diesel engine, the size distributions of soot particles show no significant difference between heavy- and light-duty diesel engines. The engine-operating mode (engine speed and load rate) does not seem to affect significantly the size distribution of soot particles. It was found that the PM from a turbo-charged diesel engine contains a higher percentage of particles smaller than 100 nm than an engine with a naturally aspirated (NA) air-inhalation system. As for gasoline engines, the PM collected after the catalytic converter has a narrower size distribution than those collected before and has a higher percentage of particles smaller than 100 nm.

Lee, Dai Woon; Kim, Sun Hui; Kim, Won-Suk; Lee, Seungho; Lim, Cheol Soo; Ryu, Jung Ho, 2001, “Size analysis of automobile soot particles using field-flow fractionation,” *Environmental Science & Technology*, **35**(6):1005–1012

Soot particles emitted from various automobile engines are analyzed for size distributions using field-flow fractionation (FFF). Soot samples are prepared for FFF analysis using a three-step procedure, where a layer of soot particles is focused between the layers of n-hexane and water, followed by dispersing of particles in water containing 0.05% Triton X-100. The mean diameters determined by FFF show similar trends with those obtained from dynamic light scattering (DLS) and scanning electron microscopy (SEM). Data from FFF are also compared with those from an on-line scanning mobility particle sizer (SMPS). SMPS size distributions extend further to larger size than those of FFF distributions, which indicates the three-step sample preparation procedure effectively disaggregates the agglomerated particles. Although the amount of particulate matter (PM) emitted from a heavy-duty diesel engine is much higher than that from a light-duty diesel engine, the size distributions of soot particles show no significant difference between heavy- and light-duty diesel engines. The engine-operating mode (engine speed and load rate) does not seem to affect significantly the size distribution of soot particles. It was found that the PM from a turbo-charged diesel engine contains a higher percentage of particles smaller than 100 nm than an engine with a naturally aspirated (NA) air-inhalation system. As for gasoline engines, the PM collected after the catalytic converter has a narrower size distribution than those collected before and has a higher percentage of particles smaller than 100 nm.

Lehmann, U.; Mohr, M., 2001, "Influence of different configurations of a catalyst and a trap on particulate emission of a diesel passenger car," *International Journal of Vehicle Design*, **27**(1–4):228–241

New particulate emission measurements performed on a diesel passenger car to see the influence of different configurations of aftertreatment systems are reported. Five combinations of a particle trap and an oxidation catalyst are investigated. These configurations are discussed in view of particulate emission, measured by number and mass. All measurements were carried out at a chassis dynamometer of the EMPA. A diesel passenger car with an IDI engine was operated at four steady state conditions. Exhaust gas was diluted in a standard constant volume sampler (CVS) device (full flow dilution tunnel). Particulate size distributions were measured with a Scanning Mobility Particle Sizer (SMPS) and gravimetric measurements were performed according to regulations. Furthermore measurements without CVS tunnel were done by using external dilution units to see the influence of the sampling method. We used a thermo desorber to distinguish volatile and non-volatile aerosol fractions and we analyzed filter samples for determination of organic soluble fraction, water-soluble fraction and sulphur content. Huge differences depending on the configuration of the aftertreatment system and load were observed. In general it was found that a large reduction of particulate emission could be obtained by using a particle trap. A catalyst converter has minor effect on particulate emission. Nucleation of new particles was observed under certain conditions depending on configuration and sampling method. 8 Refs.

Wieser, U.; Gaegauf, Ch.; Macquat, Y., 2001, "Particle emissions from wood-fired boilers - Examination of emission rates in practical use," *Technical Report No. ENET-210221*, Oekozentrum, Langenbruck (Switzerland), in German

This report made for the Swiss Federal Office of Energy (SFOE), the Swiss Agency for the Environment, Forests and Landscape (SAEFL) as well as for the air pollution inspection offices of 5 Swiss Cantons, presents the results of measurements made on 14 different types of wood-fired heating appliances and boilers with respect to their emissions of particulate matter, including units fired with wood logs, wood chippings and pellets. For comparison, the results for fossil-fuel-fired units are also quoted. The laboratory equipment and the measurement methods used are described which were used to determine the total amount of particles emitted and, in particular, the emissions of particles in the sub micrometer range. The results of the measurements made are presented and discussed in detail. A second phase of the project is described which allowed the measurement of particulate matter emissions in the field. The report is concluded with a discussion on the collection of data on particle emissions using SMPS (Scanning Mobility Particle Sizer) analysis methods, particle, size distribution and particle emission factors.

2000

Burtscher, H., 2000, "Comparison of particle emissions from different combustion systems," *Journal of Aerosol Science*, **31**(S1):S620–S621

Some examples of the properties of particles from combustion of petrol and diesel are given. The Scanning Mobility Particle Sizer (SMPS) measures size distributions. To obtain information on particle mass, a low-pressure impactor (LPI) is used in series with DMA. The DMA classifies particles according to their mobility, the LPI according to mb. 2 Refs.

Chang, Y. C.; Tseng, H. H.; Hong, G. I.; Wang, K. T., 2000, "Measurement of smoke properties of incenses made in three countries," *Journal of Aerosol Science*, **31**(S1):S488–S489

Smoke properties of incenses made in different countries are investigated. The system used consists of a flow control/conditioning console, a smoke chamber (0.035 m^3), an electrical resistance type of ignition control unit, and particle measuring instrumentation. The results showed that the smoke properties such as CMD and $MMAD_{50}$ were very similar for all three incense samples. The maximum total mass and the total number concentrations differ from each other. 3 Refs.

Harris, J. Stephen; Maricq, M. Matti, 2000, "Signature size distributions for diesel and gasoline engine exhaust particulate matter," *Journal of Aerosol Science*, **32**:749–764

The size distributions of diesel exhaust particulate matter measured from a large number of vehicles and test engines, using a variety of diesel fuels, collapse onto a single characteristic lognormal distribution, when normalized by total particle number and plotted against a scaled diameter. Distinctly different characteristic distributions are observed for direct injection and for port injection gasoline vehicles. These signature distributions are compared to numerically calculated self-preserving size distributions which incorporate fractal dimensions <3 to describe the dendritic nature of soot. However, the coagulation models alone are incapable of reproducing the observed characteristic distributions; compared to the diesel engine data they are conspicuously asymmetric and too steep on the large particle diameter side of the distribution. We discuss the possibility that soot oxidation also plays a role in determining the shape of the characteristic distributions, and the possibility that these signatures could be utilized to distinguish soot emissions from other aerosols.

Johnson, M. P.; Hilton, M.; Burrows, R.; Madden, P., 2000, "Characterization of particulates emitted from gas turbine exhausts," *Journal of Aerosol Science*, **31**(S1):S618–S619

The structure and morphology of soot particles obtained from civil gas turbines were analyzed using a variety of techniques. A Scanning Mobility Particle Sizer system (SMPS) and transmission electron microscope (TEM) were used to characterize the particle emitted from aircraft gas turbine exhausts. Both techniques determined the total soot content, including particle size distribution and qualitative and quantitative measurements. 1 Refs.

Mohr, M.; Schmatloch, V.; Zaugg, H. P., 2000, "Investigation of fine particle emissions of small oil fired burners," Proceedings *of second European conference on small burner and heating technology, ECSBT 2*, **1**:179–186, Surface, porous and catalytic burners. Burner technology. Thermo acoustics. Emissions. Sensors and burner control, Stuttgart, Germany

An experimental study on particle emissions of various small oil fired burners installed in a test boiler has been carried out using a Scanning Mobility Particle Sizer (SMPS). By means of this instrument particles were characterized by number and size in the size range between 6 nm to 200 nm. The experiments were mostly carried out under steady state conditions. A standard fuel and a low sulfur fuel were tested in the project. Number size distributions were measured as a function of air fuel ratio, fuel quality and gap between nozzle and stabilization disk. The results revealed particle concentrations at standard conditions of about 1 x 10^6 particles/cm^3 and did not show large variation between different technologies. The mode of the distributions was between 10 to 15 nm. Only a weak influence of the burner set-up on the particle concentration was observed as long as the CO concentration was within a reasonable range. On the other hand a significant effect of the fuel was found on the particle emissions.

Ristovski, Z. D.; Morawska, L.; Hitchins, J.; Thomas, S.; Greenaway, C.; Gilbert, D., 2000, "Particle emissions from compressed natural gas engines," *Journal of Aerosol Science*, **31**(4):403–413

This paper presents the results of measurements conducted to determine particle and gas emissions from two large compressed natural gas (CNG) spark ignition (SI) engines. Particle size distributions in the range from 0.01-30 µm, and gas composition were measured for five power settings of the engines: 35, 50, 65, 80 and 100% of full power. Particle emissions in the size range between 0.5 and 30 µm, measured by the aerodynamic particle sizer (APS), were very low at a level below two particles cm^{-3}. These concentrations were comparable with average ambient concentration, and were not considered in the succeeding analysis. Both engines produce significant amounts of particles in the size range between 0.015 and 0.7 mu m, measured by the Scanning Mobility Particle Sizer (SMPS). Maximum number of concentrations of about 1 x 10^7 particles cm^{-3} were very similar for both engines. The CMDs were in the range between 0.020 and 0.060 µm. The observed levels of particulate emission are in terms of number of the same order as emissions from heavy duty diesel engines. On the other hand, emissions of CO and NO_2 of 5.53 and 3.33 g kW h^{-1}, respectively, for one of the tested engines, were considerably lower than set by the standards. According to the specifications for the gas emissions, provided by the US EPA, this engine can be considered as a "low-emission" engine, although emissions of submicrometer particles are of the same order as heavy-duty diesel vehicles.

Ristovski, Z. D.; Tass, I.; Morawska, L.; Saxby, W., 2000, "Investigation into the emission of fine particles, formaldehyde, oxides of nitrogen and carbon monoxide from natural gas heaters," *Journal of Aerosol Science*, **31**(S1):S490–S491

The range of concentration levels of submicrometer particles, formaldehyde (HCHO), oxides of nitrogen (NO_x), and carbon monoxide (CO) that arises from the standard operation of four typical flueless natural gas heaters are investigated. The results showed that both fine particle mass and number emission rates are low and the mass ones are close to 0.046 ng/J. This showed that the emission of particles during the combustion of natural gas in domestic heaters do not contribute to the indoor particle concentration. Natural gas heaters are a larger contributor of organic compounds such as formaldehyde and NO_2. 2 Refs.

Zimmermann, R.; Maguhn, J.; Kettrup, A., 2000, "On-line analysis of combustion aerosols in the state of formation (900-300 degree C) at industrial incinerators," *Journal of Aerosol Science*, **31**(S1):S622–S623

On-line analytical methods were used to analyze combustion aerosols from industrial plants. Particle size distribution of the combustion aerosol were measured with a mobile aerosol measurement system, which includes an aerodynamic particle sizer (APS) and a Scanning Mobility Particle Sizer (SMPS). Results show that the measurements of the particle size distribution of the combustion aerosol probed at a 23 MW municipal waste incinerator (MWI) reveals a shift of the maximum of the particle size distribution to larger diameters upon the travel through the boiler section. The growth in particle diameter is due to reactive attachment of gas phase species and agglomeration process. 4 Refs.

1999

Harrison, Roy M.; Brear, Fred; Shi, Ji Ping, 1999, "Particle size distribution from a modern heavy duty diesel engine," *Science of the Total Environment*, **235**(1–3):305–317

The particle size distribution emitted from a modern heavy duty diesel engine was investigated. It was found that the operation of the engine test bed system, primary and secondary dilution system and instruments were stable and that particle size distributions could be measured repeatedly under specific conditions. The particle size distribution was determined at different engine speed and load. The mode in the number distribution was smaller than 25 nm at engine speed 1600 rev./min and between 40-60 nm at 2600 rev./min. Good agreement of size distributions measured by SMPS and ELPI instruments was found in the region of overlap, and with measurements made with an electron microscope and image analyser. Total particle volume concentrations calculated from SMPS and ELPI data agreed well with those estimated from filter mass data. The measured particle size distribution and total number concentration changes with the dilution conditions and humidity of dilution air. The mechanism is being investigated and preliminary results suggest that sulphuric acid is involved in homogeneous nucleation of new particles during the dilution process.

Kayes, D.; Hochgreb, S., 1999, "Mechanisms of particulate matter formation in spark-ignition engines. 3. Model of PM," *Environmental Science and Technology*, **33**(22):3978–3992

Recent health concerns over airborne particulate matter (PM) have prompted examination of the mechanisms by which PM is formed in spark ignition (SI) internal combustion engines. A study was undertaken in order to understand the effects of dilution on measured PM, to examine and model the effect of steady state engine operating conditions on engine-out PM, and to characterize the effect of transient engine conditions on particle growth and dynamics. Particle dynamics in diluted SI and compression ignition (CI) engine exhaust are examined and discussed in the context of SI exhaust dilution. Temperature measurements in the exhaust pipe and dilution tunnel reveal the degree of mixing between exhaust and dilution air, the effect of flow rate on heat transfer from undiluted and diluted exhaust to the environment, and the minimum permissible dilution ratio for a maximum sample temperature of 52 C. Measurements of PM concentrations as a function of dilution ratio, using a Scanning Mobility Particle Sizer (SMPS), show the competing effects of temperature and particle/vapor concentrations on particle growth dynamics, which result in a range of dilution ratios—from 13 to 18—where the effect of dilution ratio, independent of flow rate, is kept to a minimum and is therefore optimal in order to achieve repeatable PM concentration measurements. Particle dynamics in transit through the dilution tunnel are measured and compared to previous research. PM emissions are strongly affected by steady state engine parameters that affect global and local air/fuel ratios, the concentration of liquid fuel in the cylinder, and the availability of soot precursors. PM emissions vary by up to six orders of magnitude between the fuels tested, when at the same fuel/air equivalence ratio. Minimum PM concentrations are emitted at a global fuel/air ratio within 10% of stoichiometric, with the exact value depending on the particular fuel, and concentrations can increase by more than three orders of magnitude when the fuel/air ratio is either increased or decreased 30% from stoichiometric. Burning liquid fuel is a significant source of PM, as evidenced by the fact that open valve fuel injection increases PM emissions by up to three orders of magnitude relative to closed valve injection. Coolant and oil temperatures, spark timing, and Exhaust Gas Recirculation (EGR) affect PM through their effect on intake port and cylinder temperatures, as well as through the effect on the availability of liquid fuel in the cylinder. Particles derived from oil consumption were found to be between zero and 40% of the total PM concentration for the oils used in the present experiments. Differences in PM emissions with and without the catalytic converter are not statistically significant. Particulate number and mass concentrations plus particle sizes are addressed in the present paper, as is the correlation between PM and emissions of gaseous pollutants—hydrocarbons (HCs), oxides of nitrogen (NOx), oxides of carbon (CO and CO sub 2)—as well as oxygen and characteristic temperatures and pressures during the engine cycle. A model of PM formation via homogeneous- and heterogeneous-phase reactions, growth via condensation and adsorption/absorption of vapors, and diminution via oxidation explains the observed behavior of PM emissions with respect to each of the engine, fuel, and dilution parameters above. PM emissions during transient engine operation are generally a first-order time response with characteristic times similar to those involved in the fuel evaporation process, suggesting that PM emissions respond to instantaneous engine conditions and may be modeled using a quasi-steady state application of the model.

Kerminen, V.-M.; Makela, T.; Hillamo, R.; Rantanen, L., 1999, “Relation between particle number and mass size distribution in the diesel car exhaust,” *Journal of Aerosol Science*, **30**(S1):S777–S778

Presented are results demonstrating that detailed investigation of diesel exhaust particles requires measuring both the particle number of mass size distribution. It is shown that valuable information on diesel particle mass size distribution up to sizes of about 0.2–0.3 µm can be obtained by converting the corresponding number size distribution appropriately.

Maricq, M. M.; Podsiadlik, D. H.; Chase, R. E., 1999, “Examination of the size-resolved and transient nature of motor vehicle particle emissions,” *Environmental Science & Technology*, **33**(10):1618–1626

This paper reports mass measurements, size distributions, and the transient response of tailpipe particulate emissions from 21 recent model gasoline vehicles. Transient measurements are made for the FTP drive cycle (and limited ECE tests) using a Scanning Mobility Particle Sizer and an electrical low-pressure impactor. The particles emitted in vehicle exhaust have diameters in the 10-300 nm diameter range, with a mean diameter of about 60 nm. Particle emissions during the drive cycles occur as narrow peaks that correlate with vehicle acceleration. Cold start emissions generally outweigh those from a hot start by more than a factor of 3. Particulate mass deduced from the transient distributions agrees semiquantitatively with gravimetric measurements. Tailpipe particulate emissions from the recent model gasoline vehicles tested are very low, with mass emission rates ranging downward from 7 mg/mi for a light-duty truck during the cold start phase of the FTP drive cycle to less than or equal to 0.1 mg/mi during phase 2 for nearly half of the test vehicles. Three high-mileage (>100 K mi) test vehicles exhibited similarly low particulate emission rates. The FTP-weighted 3-bag average is under 2 mg/mi for all the conventional gasoline vehicles tested.

Maricq, M. M.; Podsiadlik, D. H.; Chase, R. E., 1999, “Gasoline Vehicle Particle Size Distributions: Comparison of Steady State, FTP, and US06 Measurements,” *Environmental Science & Technology*, **33**(12):2007–2015

Factors influencing the number and size of tailpipe particles from port injection, spark ignition vehicles are examined by comparing emissions recorded during steady-state operation and those obtained from FTP and US06 drive cycles. Size distributions are measured using the Scanning Mobility Particle Sizer (SMPS) and the electrical low-pressure impactor (ELPI). Steady-state particulate emissions are examined as a function of vehicle speed and air to fuel ratio. The emission rates increase moderately with increasing speed but climb steeply with decreasing A/F. This is consistent with the observations from transient drive cycle measurements where particulate emissions occur predominantly during periods of heavy acceleration. As expected from the more aggressive speed and acceleration of the US06 cycle, the per mile particulate emission rates are higher than for phases 2 and 3 of the FTP. For the eight vehicles tested, the US06 mass emissions range from 1.2 to 9.6 mg/mi. Use of a US06-compliant calibration leads to a factor of 2 reduction of particulate emissions, in both number and mass, over the drive cycle.

1998

Abdul-Khalek, I. S.; Kittelson, D. B.; Graskow, B. R.; Wei, Q.; Brear, F., 1998, “Diesel exhaust particle size: measurement issues and trends,” *Proceedings of the 1998 SAE International Congress & Exposition, In-Cylinder Diesel Particulate and NOx Control SAE Special Publications, SAE*, Warrendale, PA, USA, **1326**:133–145

Measurements of exhaust particle size distribution and number concentration produced by a modern, low emission diesel engine were made. The influences of operating conditions, an exhaust catalyst, and dilution conditions were determined. The engine was tested under the operating conditions of the ISO 8 and 11 Mode tests. Measurements were performed on the exhaust of a medium-duty, turbocharged, aftercooled, direct injection Diesel engine, using a mini-dilution system, Scanning Mobility Particle Sizer (SMPS), and condensation particle counter (CPC). In the case of the engine catalyst studies, an electrical aerosol analyzer (EAA) and a condensation nucleus counter (CNC) were used. Results show that number size distribution are bi-modal and log-normal in form. In most cases, more than half of the particle number are present in the nuclei mode. 27 Refs.

Ahmed, S. H.; Hayat, S. O., 1998, “Effect of ashless additive technologies on the number and size distribution of fine particles emitted from diesel engines,” *Diesel engines - particulate control. Proceedings*, pp. 1–13, 105 page(s), Book analytic

The Scanning Mobility Particle Sizer was used in a comparative study of two diesel fuels, (a) low sulphur EN 590 diesel and (b) ultra low sulphur 'city diesel' and several ashless additive technologies to determine their effect on fine particle emissions from a heavy duty single cylinder and a light duty multi-cylinder engine. The two fuels provided significantly different particle number emissions but similar size distributions. An additive formulation containing a non metallic ashless combustion enhancer provided significant reductions of between 45% and 85% in particle number emissions, in both the test fuels with no shift in the particle size distribution. The multifunctional additive package containing a dispersant and a lubricity agent did not significantly alter the number of particles emitted or the particle size distribution.

Bach, C.; Heeb, N.; Mattrel, P.; Mohr, M., 1998, “Effect-based assessment of exhaust emissions from automobiles,” Report 58 page(s), Swiss Federal Laboratory for Materials Testing and Research (EMPA), Report No. EMPA—160928/2

As a result of current exhaust emission specifications for gasoline and diesel vehicles, alternative or reformulated energy sources cannot be simply compared with each other on the basis of the regulated test and measuring methods. For this reason a measuring procedure for an 'effect-based assessment of exhaust emissions' has been developed together with a rating matrix. Subsequently, this was used as an example on one vehicle type with a gasoline, natural gas and diesel engine. The aim of the project was to compare the exhaust emissions with respect to the ozone formation potential, greenhouse gases, acid formation, carcinogenic gases, and particles as well as energy consumption. The integral measurements were performed by using the conventional standard bag method, gas and liquid chromatography, and a Scanning Mobility Particle Sizer (SMPS). In order to be able to investigate the exhaust emissions during critical conditions of the cycle such as cold start or acceleration procedures, measurements were carried out continuously as well. For these tests, the conventional analyser for the regulated air pollutants were used as well as an on-line mass spectrometer for the measurement of methane, ethane, benzene, xylene and toluene. The report summarizes the results.

Graskow, B. R.; Kittelson, D. B.; Abdul-Khalek, I. S.; Ahmadi, M. R.; Morris, J. E., 1998, “Characterization of exhaust particulate emissions from a spark ignition engine,” *Proceedings of the 1998 SAE International Congress & Exposition, In-Cylinder Diesel Particulate and NOx Control SAE Special Publications, SAE*, Warrendale, PA, USA, **1326**:155–165

Several experiments were undertaken to measure and characterize exhaust particulate emissions from a spark ignition engine. Experiments were performed using three different fuels with measurements made both upstream and downstream of the catalytic converter. Emissions were characterized in terms of number-weighted break, specific particle emissions and particulate size distribution. 26 Refs.

Ristovski, Z. D.; Morawska, L.; Bofinger, N. D.; Hitchins, J., 1998, “Submicrometer and Supermicrometer Particulate Emission from Spark Ignition Vehicles,” *Environmental Science and Technology*, **32**(24):3845–3852

Particulate emissions from 11 gasoline-powered and 2 liquefied petroleum (LPG)-powered passenger vehicles were characterized during the Accelerated Simulation Mode driving cycles on a chassis dynamometer. The test fleet consisted of 10 catalyst-equipped vehicles operated with unleaded gasoline (5 Ford Falcons and 5 Holden Commodores), 2 LPG-powered vehicles (both Ford Falcons), and 1 older type noncatalyst vehicle operated with leaded gasoline. Particulate characterization included determination of total particulate number concentration and size distribution using the Scanning Mobility Particle Sizer (SMPS) and the aerodynamic particle sizer (APS). The average particle number concentrations in the SMPS range for all modes was lower for Ford Falcons and somewhat higher for Commodores, with values of 1.5×10^4 and 4.1×10^4 cm^{-3}, respectively. This difference is significant and was observed for all modes. The number concentration levels were higher for the LPG-fueled cars (8.4×10^4 cm^{-3}) and for the leaded gasoline-powered vehicle (7.9×10^4 cm^{-3}). There was not a significant variation in particle count median diameter in the SMPS and the APS ranges, either for different operating conditions of the vehicles investigated or between different vehicle groups. The observed size distributions were bimodal with average values of CMD ranging from 39.1 to 60.2 nm in the SMPS range and from 0.9 to 1.4 µm in the APS range. The results obtained from this study can be used as a first order estimation toward emission inventories for vehicle groups included in the investigations.

1997

Matter, U.; Siegmann, K., 1997, “The influence of particle filter and fuel additives on turbo diesel engine exhaust,” *Journal of Aerosol Science*, **28**(S1):S51–S52

Particulate emission from modern turbo diesel engines on test benches is investigated. Photoemission sensors, an aethalometer and a Scanning Mobility Particle Sizer (SMPS) are employed to characterize the particles, together with filter analyses of sampled soot. Commercially available fuel additives and particle filters are investigated in their ability of reducing particulate emission. Promising techniques of sensing particulate diesel exhaust are evaluated.

1996

Christensen, K. A.; Livbjerg, H., 1996, “Field study of submicron particles from the combustion of straw,” *Aerosol Science & Technology*, **25**(2):185–199

The evolution of small aerosol particles accompanying the combustion of straw for energy production is investigated. A sampling equipment specially designed for field measurements is described and characterized. The aerosol is studied by low-pressure cascade impactor and Scanning Mobility Particle Sizer, the particle morphology by transmission electron microscopy, and the chemical composition by energy dispersive x-ray analysis. The combustion gas contains 3-500 mg/Nm^3 of submicron particles with a mean diameter of approximately 0.3 µm. The particles consist of almost pure potassium chloride and sulphate. The formation mechanism is analyzed by a theoretical simulation of the chemical reactions and the aerosol change during cooling of the flue gas. It is concluded that some sulphation of KCl occurs in the gas phase although the sulphate concentration is much lower than predicted by an equilibrium assumption. The theoretical simulation proves that the fine mode particles can be formed by homogeneous nucleation of either KCl or $K_2 SO_4$ as the first step and further growth occurs by coagulation and diffusive condensation of both KCl and $K_4 SO_4$ on existing particles. 25 refs., 13 figs., 2 tabs.

Owens, T. M.; Biswas, P., 1996, “Vapor phase sorbent precursors for toxic metal emissions control from combustors,” *Industrial and Engineering Chemistry Research*, **35**(3):792–798

A bench scale system incorporating a high temperature flow reactor has been utilized to study the reaction of metallic species and sorbent compounds. The reaction and interaction between a lead precursor and a vapor phase silica precursor is studied. The effect of chlorine and the effect of sorbent to metal feed ratio on lead speciation and size distribution is determined. The size distributions of the reacted compounds are measured by a Scanning Mobility Particle Sizer (SMPS) and an optical particle counter (OPC). The product powders are also collected and their compositions established by X-ray diffraction (XRD) or, if an amorphous powder is collected, by infrared and raman spectroscopy. Experiments have been performed at 500, 750, 1,000, and 1,250 C and for reactor residence times of 0.5--1.0 s. For example, at 750 C, for a lead feed in conjunction with a vapor phase silica precursor compound, the mean particle size exiting the reactor is significantly larger than for a lead only feed or a silicon only feed. The composition of the resulting aerosol is determined, via infrared and Raman spectroscopy, to be lead silicate, $PbSiO_3$. Higher temperature results are similar. At lower temperatures, silica particles are not formed in the reactor. Higher silica precursor feed rates result in particles large enough for capture by conventional pollution control equipment.

Wu, C.-Y.; Arar, E.; Biswas, P., 1996, “Mercury capture by aerosol transformation in combustion environments,” Book Monograph, Published at Pittsburgh, PA, USA, the 1996 Annual Meeting of Air and Waste Management Association 89, Nashville, TN, USA

Mercury released from coal combustors and waste incinerators poses a potential environmental concern. Unlike most other heavy metals that are emitted in particulate form, mercury has been reported to be released mainly in the elemental vapor phase that is not effectively captured in typical particulate control devices. In this work, we examine the oxidation of mercury in air at high temperature environments. The objective is to effectively transform mercury into mercury oxide which has a higher possibility to form particles because of its lower vapor pressure. The study was conducted in a new reactor with real-time measurement of particle size distribution (by Scanning Mobility Particle Sizer) and composition analysis by x-ray diffraction for particles on filters and by Cold Vapor Atomic Absorption Spectroscopy for gaseous species collected in impingers). Temperature was varied from 320 degree C to 1200 degree C and residence time was varied from 1.5 s to 45 s. Although oxidation was observed when the residence time was increased, the experimental results showed that the oxidation rate was too slow to be effective for mercury capture in practical combustion systems. Studies are needed for alternative approaches to capture mercury vapor such as the use of novel sorbent materials.

1995

Biswas, P.; Owens, T. M.; Wu, C. Y., 1995, “Control of toxic metal emissions from combustors using vapor phase sorbent materials,” *Journal of Aerosol Science*, **26**:S217–S218

In this paper, results of experiments on the evolution of the lead aerosol size distribution in different environments are reported to develop better insights into particle formation and growth mechanisms. The use of vapor phase sorbents for metals capture in high temperature gas streams are also reported. The experimental system used in this work consists of a flow reactor with real time measurement of particle size distributions (Scanning Mobility Particle Sizer) at the exit of the reactor. Lead is introduced by atomizing a solution of lead acetate. Depending on the experiment, chlorine is also introduced into the system. The sorbent is inlet to the reactor in the vapor form, carried in an argon stream. The particles are collected at the exit of the reactor for chemical characterization by x-ray diffraction. Experiments were conducted for a range of temperatures (500 to 1200 degree C), flow rates and inlet concentrations.

1994

Huglin, Ch.; Gaegauf, Ch.; Burtscher, H., 1994, “Size distribution and photoelectric activity of particles in wood combustion exhaust,” *Journal of Aerosol Science*, **25**(S1):113–114

In order to study particulate emissions from wood combustion, size distributions of two different systems has been measured. A wood stove in different phases of the combustion and a wood chip burner have been used for these measurements. Size distribution of emissions were found to differ significantly in different phases of wood combustion.

1992

Hautanen, Jukka; Kilpelainen, Markku; Kauppinen, Esko I.; Jokiniemi, Jorma K.; Lehtinen, Kari E. J., 1992, “Electrical Agglomeration of Fly Ash Particles,” *Aerosol Science*, **23**(S1):S783–S786

Electrical agglomeration of charged aerosol particles in alternating electrical field has been studied. Experimental system and preliminary results are presented.

Joutsensaari, Jorma; Kauppinen, Esko I.; Ahonen, Petri; Lind, Terttaliisa M.; Ylatao, Sampo I.; Jokiniemi, Jorma K.; Hautanen, Jukka; Kilpelainen, Markku, 1992, “Aerosol Formation in Real Scale Pulverized Coal Combustion,” *Aerosol Science*, **23**(S1):S241–S244

Aerosol formation in pulverized coal combustion have been studied experimentally at the real scale power plant. Combustion aerosol mass and number size distributions have been determined, when burning bituminous coal from Poland. Mass size distributions have been measured by low pressure impactor and number distributions by differential electrical mobility (DMA) method.

Makela, Jyrki M.; Aalto, Pasi; Gorbunov, Boris Z.; Korhonen, Pekka, 1992, "Size Distributions from Aerosol Spark Generator," *Aerosol Science*, **23**(S1):S233–S236

An aerosol spark generator for producing ultrafine particles from metals is described. The aerosol particle size distributions from the spark generator have been measured by both Diffusion Battery-CNC and DMA-Electrometer systems. The average diameter of the generated particles can be varied to be between 2 and 15 nm. The measurements on the particle size distributions are described.

Patschull, J.; Roth, P., 1992, "Charge and Size Distribution of Particles Emitted From a Di-Diesel Engine," *Aerosol Science*, **23**(S1):S229–S232

In diesel engines solid particle phases are formed as a result of incomplete combustion in fuel rich zones of the diffusion-controlled spray combustion. The whole process is composed of particle inception and surface growth associated with agglomation of the monomeres to irregularly shaped particle aggregates. Furthermore, diesel particles are electrically charged by electrons and ions produced during the involved chemical reactions. As the flame ionization causes a bipolar diffusion charging very early in the engine cycle, the contact electrifications by surface interactions and the thermoelectric charging might lead to an unbalanced charge distribution. The present paper reports on some measurements of particle charge and size distribution performed on the diluted diesel exhaust obtained under different engine operation conditions. The size distributions of the particles as well as the fraction and the balance of naturally charged particles were determined from electrical mobility measurements. Furthermore, the number of elementary charges per particle was investigated by classifying and counting particles of a discrete mobility class. The evaluation of these measurements resulted in charge distributions of the naturally charged particles.

1983

Neville, M.; McCarthy, J.F.; Sarofim, A.F., 1983, "Size Fractionation of Submicrometer Coal Combustion Aerosol for Chemical Analysis," *Atmospheric Environment*, **17**(12):2599–2604

The application of an electrostatic classifier for discrete size classification of sub-um fly-ash particles was examined for the purpose of determining the size dependence of elemental concentration. From transmission electron microscopy studies, the size fractionated output for these particles from the electrostatic classifier was found to have larger effective mean diameter and a broader distribution than would be expected from the theory for singly charged particles. Four discrete size cuts of the sub-um particles, produced from the combustion of Montana lignite in a laboratory scale combustion system, with mean diameters of 10, 20, 30 and 40 nm were analyzed by INAA. The concentration of the volatile and trace species which condense well after the birth of the sub-um particles (Neville and Sarofim, 1983) as the combustion gases are being cooled were found to be systematically enriched with decreasing particle size. The observed d^-1 relationship is consistent with a hypotheses that the volatile and trace elements condense on the surface of the sub-um particles with the rate of deposition being controlled by mass transfer.