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Time Resolved Size Distributions of Test Smokes and Nuisance Aerosols

Abstract

An electrical low-pressure impactor (ELPI) has been used to measure the size distribution of various test smokes and nuisance aerosols generated in the fire emulator/detector evaluator (FE/DE). Previously reported size results were time-averaged values with sampling times on the order of five minutes required to collect a weighable amount. The ELPI is a 12-stage cascade impactor that separates particles between an aerodynamic diameter size range of 0.03 μm to 10 μm, which covers a wide range of particle sizes of interest in smoke alarm research. A complete size distribution is recorded every 10 s. The size distributions of several test smokes including: propene soot, smoldering cotton, and smoldering wood smoke were measured throughout smoke alarm exposure tests. The size distribution of several nuisance aerosols including: dust, cigarette smoke, and cooking smokes were also measured. Additionally, comparisons were made between the ELPI results and results from a tapered element oscillating microbalance and the measuring ionization chamber.

Introduction

Smoke alarm response is a function of the amount of aerosol present in the sensing volume, and the properties of that aerosol. The particle size distribution of an aerosol is a characteristic that influences the response of photoelectric (light scattering alarms), ionization alarms, and light extinction-based alarms. Size distribution information has been gathered on smokes used in fire alarm studies and test methods [1-4]. The range of the size distributions of all aerosols of interest covers nanometer sized particles to particles potentially greater than 10 micrometers, or upwards of 4 orders of magnitude. Low-pressure impactors can cover a range from the largest size of interest, down to less than 50 nanometers. Here, the response of an electrical, low-pressure impactor (ELPI), developed at the Tampere University of Technology, [5] was used to measure temporal

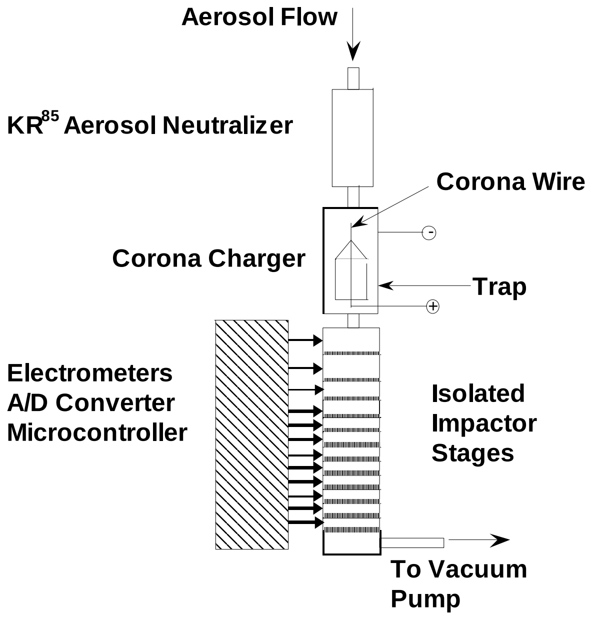

Figure 1. Schematic of the ELPI.

size distributions of several test smokes generated in the fire emulator/detector evaluator. It measures the size distribution over an aerodynamic diameter size range of 0.03 – 10 µm in 12 discrete channels. It has a temporal resolution on the order of 5 s. A schematic diagram of the instrument is given is Figure 1, and it is commercially available from DEKATI LTD[1].

A performance evaluation of the instrument was conducted, and results of the number distribution compared favorably with another standard aerosol sizing instrument [6]. The instrument consists of a 12-stage multi-orifice, low-pressure impactor that classifies particles according to their aerodynamic size (equivalent diameter unit density sphere.) Beginning at the first stage, particles of a narrow size range (defined by a cut-off size) impact on that stage's collection plate, while smaller particles move on to the next stage. The process repeats itself until the last stage is reached. The flow through the instrument is 10 l/min. Typically, cascade impactors rely on a gravimetric determination of the amount of particles collected on any stage, thus the sampling time must be sufficient to gather a weighable amount of material on each stage. This impactor is unique in that it detects particles that impact on the different stages by measuring the charge transferred to the stage from the elemental charges carried by the particles. Aerosol particles will achieve a statistically average charge level based on particle diameter, initial charge state, and exposure to charging mechanisms. The ELPI conditions the aerosol to such a state by a two-step process. The initial charge state is forced to an equilibrium, Boltzmann charge distribution by passing the aerosol through

[1] Certain commercial products are identified to adequately describe the experiment. This in no way implies endorsement from NIST.

a charge neutralizer (external to the ELPI). Then, a high-voltage corona wire unipolar charger puts known a excess charge on the aerosol particles based on their size and the residence time the aerosol remains in the charging section. Excess ions and very small charged particles are removed by an ion trap just past the charger. Each impactor stage is electrically isolated and connected to an electrometer. As aerosol particles impact on the various stages, they transfer their charges and a current is measured. From the current measurement, impactor stage cut-off sizes, flow through the instrument, and the relationship between the particle size and average charge, the number of particles that impact each stage is computed and the number size distribution is characterized. The number distribution can be converted into diameter, surface area, or mass distribution, etc., and the total number, or mass (assuming spherical unit density particles) can be computed.

Experimental

All aerosols were generated and sampled from the fire emulator/detector evaluator, described in detail elsewhere [7,8]. Briefly, it is a single pass wind tunnel that is used for smoke alarm research. The aerosols were isokinetically sampled from the center of the duct in the test section, below the measuring ionization chamber, which in turn, was mounted on the duct ceiling. The aerosol passed through a Kr^{85} neutralizer then was split between the ELPI and other aerosol measurement instruments including a tapered-element, oscillating microbalance (TEOM), an instrument that records real-time mass concentration of the aerosol. The TEOM has an estimated standard uncertainty of 0.5 mg/m^3.

The test aerosols examined include soot from the propene smoke generator attached to the FE/DE. Smoldering cotton and smoldering beech wood block smokes similar to the smolder sources in EN 54 part 9 [9] were generated. Nuisance aerosols included cigarette smoke from two lit cigarettes placed inside the FE/DE, ISO test dust injected into the FE/DE from a constant dust feeder, and smoke from bread toasting in a toaster placed inside the FE/DE duct. Full details on the methods of smoke and nuisance aerosol generation are provided in [8].

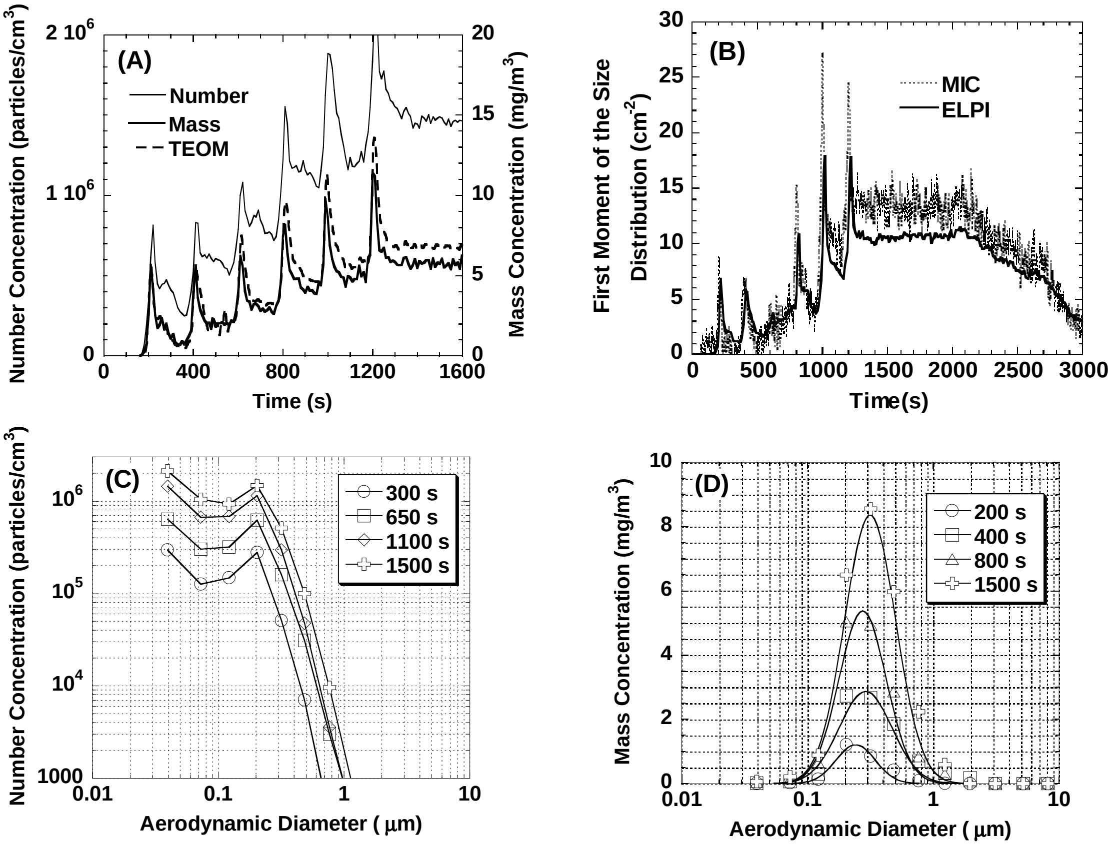

Figure 2. Results for cotton smolder smoke.

Results and Analysis

Figure 2 shows the results for cotton smolder smoke. At 200 s intervals, sets of wicks (two wicks for the first four intervals, and four wicks for the next two intervals) were ignited. Figure 2A shows the number and mass concentration from the ELPI, and the mass concentration (aerosol density assumed to be 1.0 g/cm^3 here, and likewise the same for subsequent aerosols, except ISO dust) from the TEOM. The ELPI mass concentration follows the TEOM mass concentration trend, though it recorded a lower value. Figure 2B shows a comparison of the measuring ionization chamber (MIC) results and the ELPI diameter averaged size distribution. The MIC results were converted into the first moment of the size distribution (the first moment is equal to the sum of all particle diameters, and on a unit volume basis it has the units of {length}$^{-2}$.) from the correlation provided by Fissan, *et al.* [10] and their chamber constant of 0.033 cm^2 (standard uncertainty 0.005 cm^2.) The ELPI data reduction program was used to compute the first moment of the size distribution. The MIC first moment was slightly

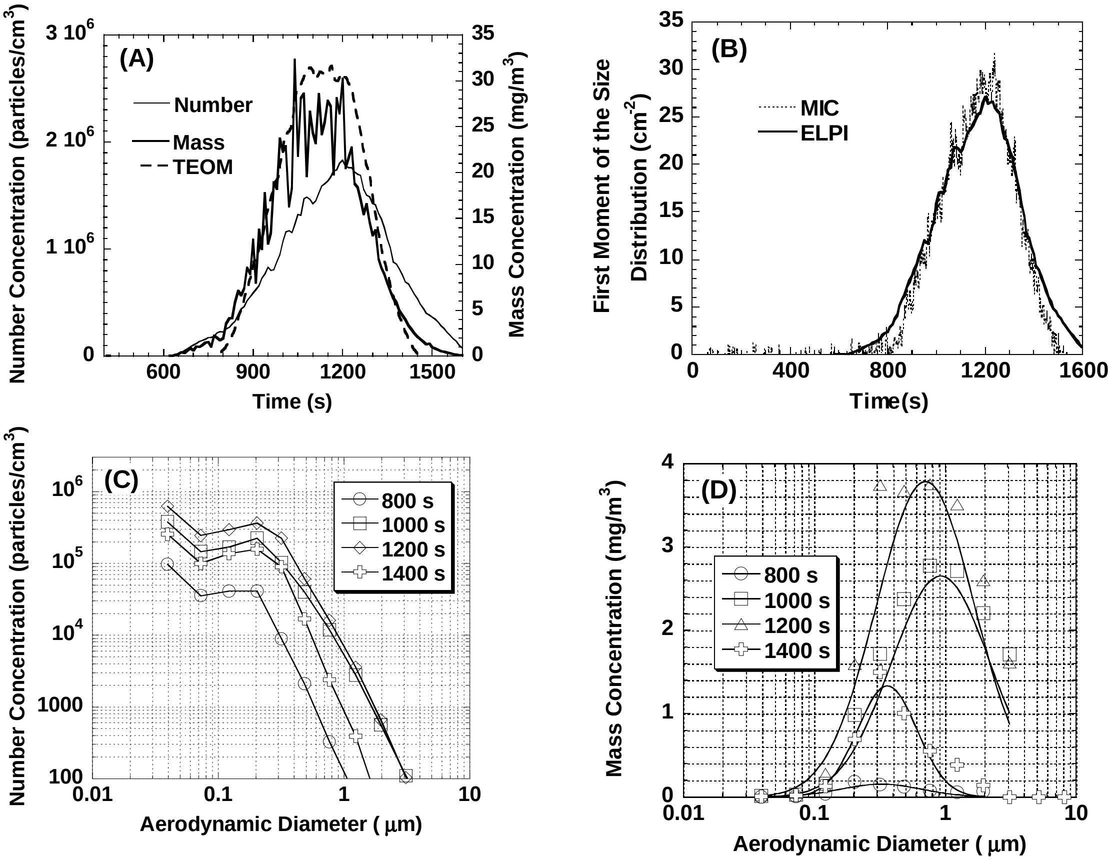

Figure 3. Results for wood smoke.

higher than the ELPI first moment, but it is within the uncertainty of the estimate. The difference could be due in part to the fact that the ELPI does not count particles below 30 nm. Figure 2C shows the number distribution at four discrete times. The number of particles (per unit volume) that were impacted on a particular stage are plotted against the geometric midpoint of the stage cutoff size and the stage above it. The shapes of the four distributions are similar suggesting the size distributions were similar, and only the concentrations were different. The data also suggest the size distribution is bimodal with a number peak at a size range below the lowest resolvable size. Figure 4D shows the mass distribution at four discrete times. The smooth curves through the data points are best-fit curves fitted to a lognormal size distribution. The mean size and the width of the distribution appear essentially constant at those times.

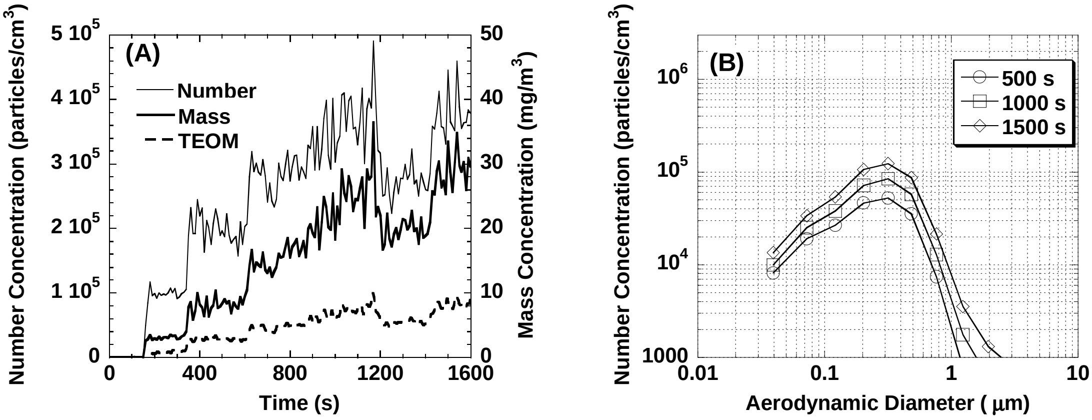

Figure 4. Results for soot.

Figure 3 shows the results for wood smoke. Figure 3A shows the ELPI mass peak was lower than the TEOM peak, but the trends were the same. Figure 3B shows that the first moment calculations were similar. The number distribution at four different times is plotted in Figure 3C. Similar to the cotton smolder smoke, the wood smoke appears to have a bimodal number distribution. Figure 3D shows the mass distribution at four times. The mass mean diameter appears smaller at the beginning and end of the smoke production (800 s and 1400 s), and overall was larger than cotton smolder values.

Figure 4 shows the results for soot. Figure 4A shows that the ELPI and TEOM mass concentrations differ by upwards of 200 %. Figure 4B show the number distribution at three discrete times for reference. There are several issues concerning measuring soot in the ELPI. First, soot is characterized as a fractal agglomerate made up from a number of primary particles typically on the order of 30 nm in diameter [11]. Using a cascade impactor for soot agglomerates is much more unforgiving than for more compact aerosols. The gross size of an agglomerate is larger than its aerodynamic size even though the bulk density of soot primary particles is close to 2 g/cm^3 [12]. So, even if the aerodynamic diameter is known, an apparent density is needed to compute the particle mass from the aerodynamic diameter. Furthermore, ELPI software assumes the net charge carried by a particle is determined by the spherical size of the particle. Soot agglomerates tend have a higher charge state than what is estimated by their aerodynamic diameter, which leads to an over-prediction of the number of soot

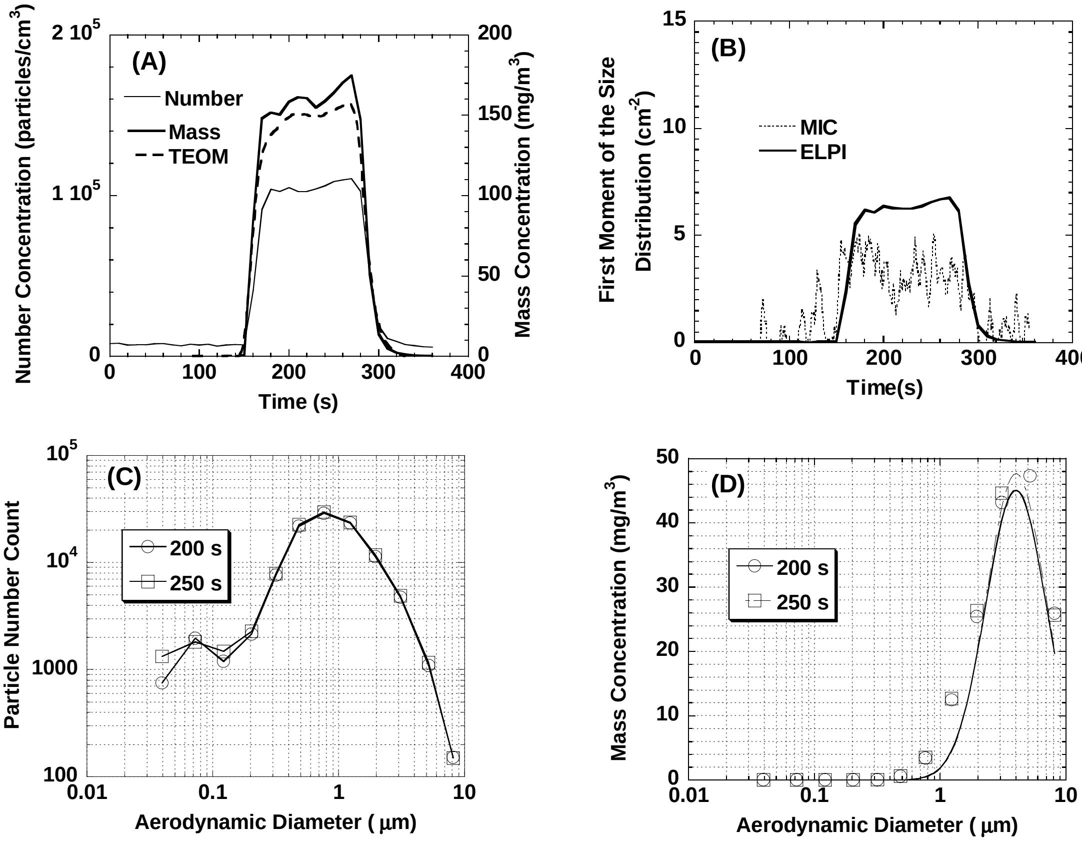

Figure 5. Results for ISO test dust.

particles impacted on a stage for a given current reading [13]. Van Gulijk *et al.*, describe a model that, with further development, could improve the ELPI data reduction scheme for soot [13].

Figure 5 shows the results for ISO fine test dust. The ELPI data was reduced using the known particle density of 2.65 g/cm^3 for the ISO dust. The ELPI and TEOM mass concentrations were nearly identical. The MIC first moment tended to be less than the ELPI first moment, which could be due to differences in concentration arising from the two sampling heights and the uncertainty in the calculated values. The number distribution shows a large peak at about 0.8 µm, which is attributed to the dust, and a flat section at smaller sizes, which was probably due to ambient aerosol in the FE/DE flow. The mass distribution shows a peak a 4.0 µm.

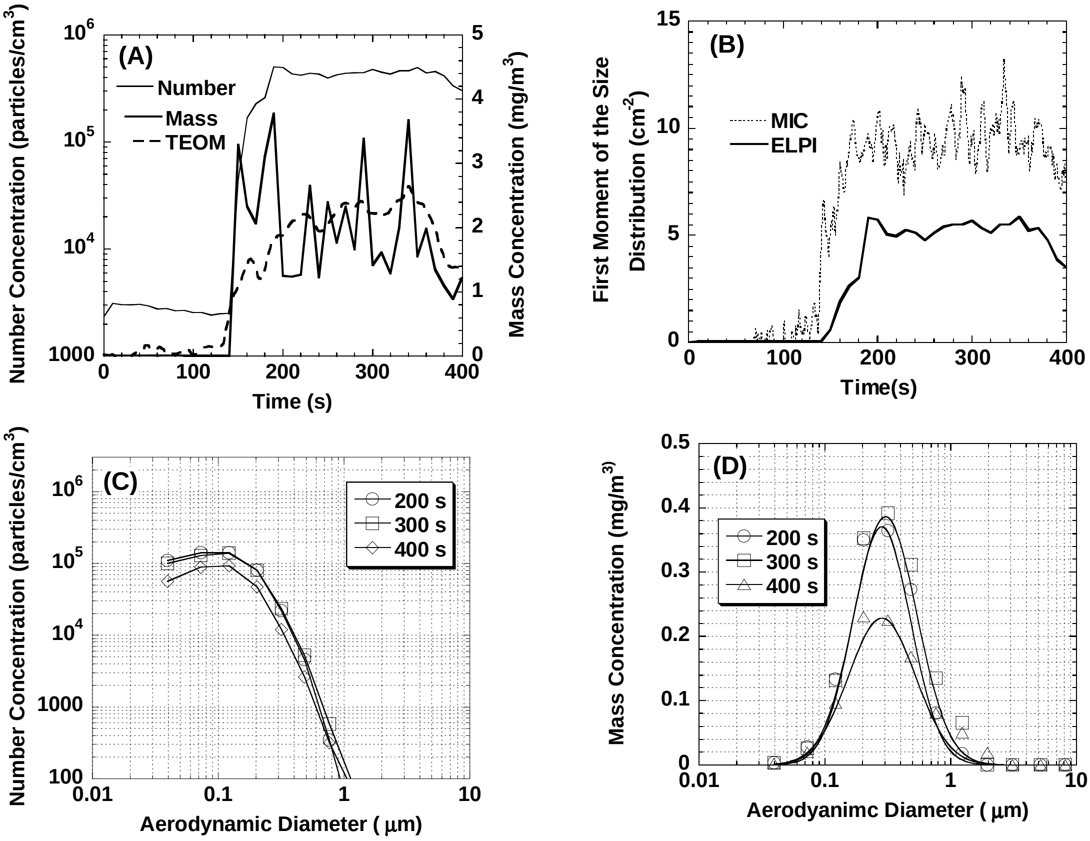

Figure 6. Results for two cigarettes.

Figure 6 shows the results for cigarette smoke from two lit cigarettes placed inside the FE/DE. The ELPI and TEOM mass concentrations were similar; the fluctuations in the ELPI mass concentration were most likely due to the ELPI electrometer gain selection. The MIC first moment was larger than the ELPI value. Figure 6C shows that the number concentration from the ELPI misses a lot of particles smaller than 0.03 µm, which is probably main the cause of the moment differences. The mass mean diameter for the cigarette smoke was about 0.3 µm.

Figure 7 shows the results for one slice of white bread toasting in a toaster. The ELPI and TEOM mass concentrations are quite different before 300 s. The ELPI indicated mass earlier than the TEOM. After 300 s the two instrument mass concentration measurements agreed much better. The first moment calculations were far apart until about 320. Clearly, the nature of the toasting bread aerosol was causing problems with

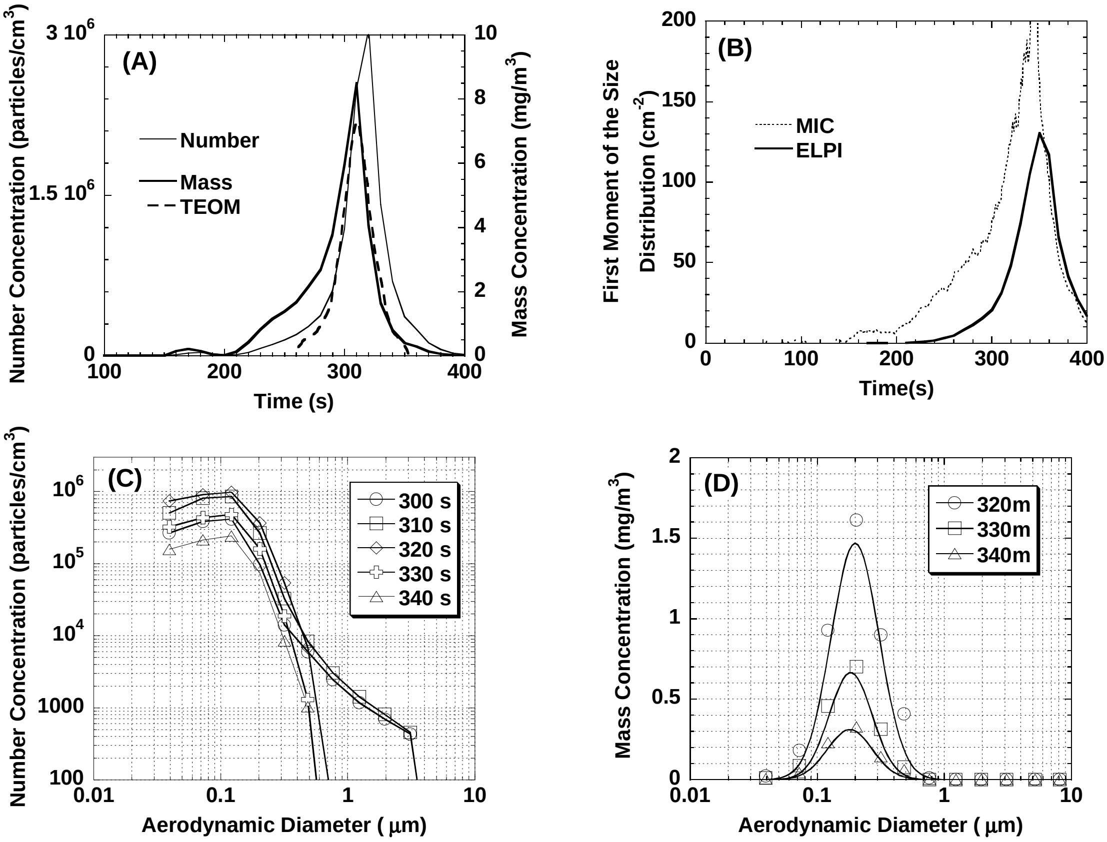

Figure 7. Results from toasting bread.

the instrument data reduction scheme. The number distribution shows the effects of this error. A tail at large particle sizes was evident at times below 330 s, which leads to the mass concentration and first moment errors. Figure 7D shows the mass distribution using the data from stages with a cut-off size less than 1 µm.

Conclusions

The ELPI showed that it could measure the size distributions of several test aerosols used in smoke detector research. It provided temporally resolved results, and in many cases compared favorably with other measurements. While the ELPI covers a very wide size range, the fact that it does not measure the size distribution below 30 nm means some aerosols are not fully characterized. The commercial ELPI does have the provision of an extra 13th stage back-up filter that collects all particles below 30 nm, and which would provide more quantitative information on the concentration of the small particles. There were some problems with soot aerosol, and the early aerosol produced from the toasting bread, that led to suspect results. For the most part, careful attention to the operation of the instrument, and interpretation of the results, yields valid size distribution information.

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