Excellence in Particle Measurements

MMEA M4.5.1.4

Measurement of high temperature aerosol using ELPI+

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DEKATI Ltd, Tykkitie 1, 36240 Kangasala, FINLAND
tel +358(0)3-3578100, fax +358(0)3-3578140, email: sales@dekati.fi http://www.dekati.fi

Contractors

DEKATI Ltd.
Tykkitie 1
FI-36240 Kangasala
FINLAND
Tel. +358 3 3578100
Fax +358 3 3578140
Email sales@dekati.fi
www.dekati.com

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MMEA Programme FP5 Deliverable 4.5.1.4. focuses on the high temperature aerosol measurement. In the setup the ELPI+ detector part (impactor) has been removed from its standard housing and put into a heating cabinet. This setup allows hot aerosol measurements without dilution and without uncertainties related to that.

This document describes the construction and calibration of the system and presents an example measurement data from a Natural gas engine measurement.</td></tr>
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1 Introduction

A typical combustion aerosol solid particle measurement system consists of a dilution system and a measurement instrument. Dilution is used to decrease the aerosol temperature and concentration in a controlled way, i.e. without particle losses and without volatile and semivolatile material condensation and / or nucleation.

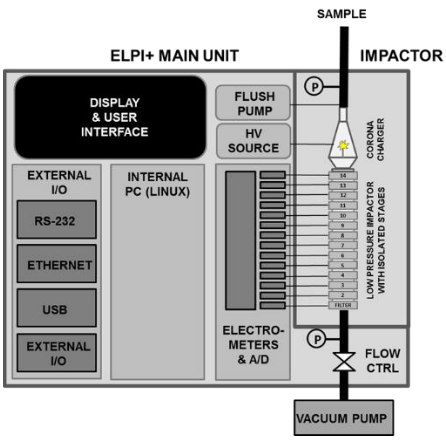
The drawback with the dilution system is that it makes the system more complex (more parts and devices, connections, need for dilution air and so on) and it increases the measurement uncertainties: Dilution ratio is not exactly as specified, the system has losses and the system may even change the particles.

Yet the other problem with low particle concentrations is that the dilution ration might decrease the particle concentration too much. The practical minimum for typical two-stage dilution system dilution factor is about 1:20. After high-end emission cleaning systems this might decrease the diluted aerosol concentrations below the measurement instrument detection limit.

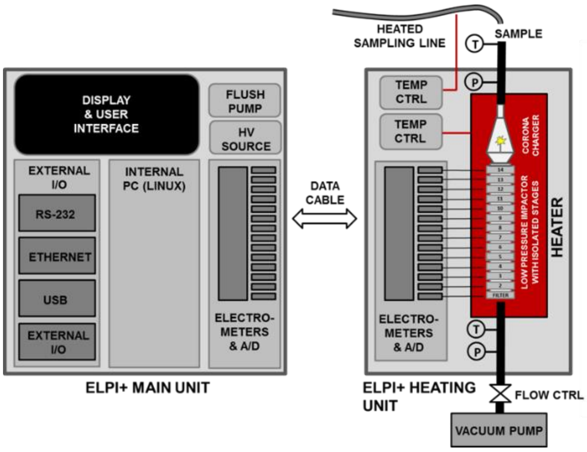
To overcome these problems a new and unique measurement system was developed for high temperature, low concentration aerosol measurements: High Temperature ELPI+ is system that can measure the particles at flue gas stack or vehicle tailpipe conditions, that is, at high temperature and without dilution and without sample cooling.

2 Instrumentation: ELPI+ vs. High Temperature ELPI+

ELPI+, Electrical Low Pressure Impactor, is a real-time particle size spectrometer. Its operation is based on particle charging in a diffusion charger and particle size classification in a 14-stage low pressure impactor. Each isolated impactor stage is connected to an electrometer measuring the electrical current carried by particles collected to a corresponding impactor stage:



In High Temperature ELPI+ the detector part (Charger-Impactor assembly) is removed from its normal housing and placed into a separate heating unit:



Heating unit contains the impactor and charger heater, insulation, temperature controls and a separate electrometer unit measuring the currents from the heated impactor. From there the measurement signals are transferred to the actual ELPI+ unit using a data cable. Further data processing and calculations are performed like in the normal ELPI+ measurement.

3 High Temperature ELPI+ Specifications

The following table lists the key specifications of the system:

Temperature controller	2 x CAL-3300 PID controllers
Max. temperature	180°C for impactor 250°C for external heater (sampling line)
Heater power	500W for impactor heater Max. 1000/500W for External heater (230V/110V)
Warm-up time	Approximately 4 h
Temperature measurement	Sample inlet Heater After impactor
Pre-set calibration temperatures	60, 120 and 180°C Other calibrations can be calculated

4 Effect of temperature to ELPI+ calibration

Impactor heating affects its calibration, and this should be taken into account in instrument calculations. Impactor cutpoint calculation is based on stage pressure measurements and known (calibrated) Stokes numbers according to article

Hillamo, R. E., & Kauppinen, E. I. (1991). On the performance of the Berner low pressure impactor. Aerosol Science and Technology, 14(1), 33-47

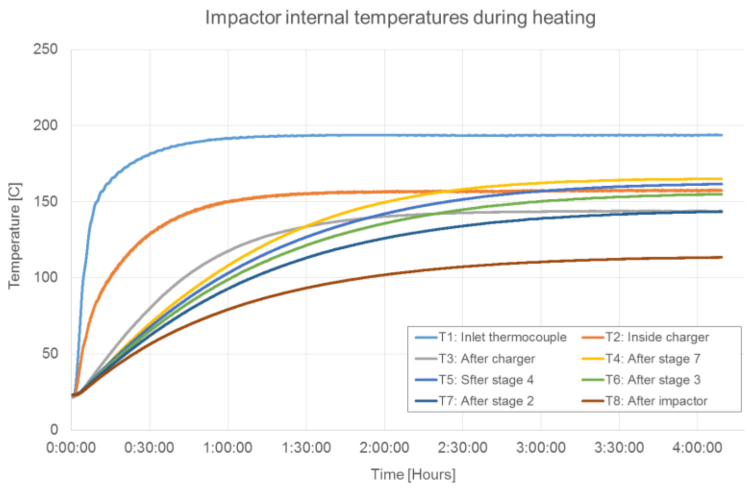
In high temperature measurements the gas flow rate, jet velocities in impactor nozzles, gas viscosity and mean free path are changed according to abovementioned article. It should be noted that the charger efficiency is assumed to be unaffected by the temperature.

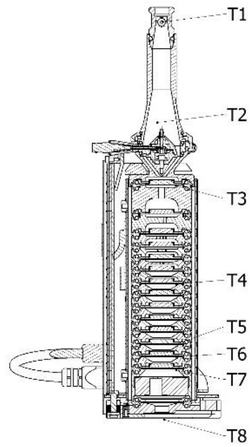
An example of the temperature effect is seen in the following table:

	21C	**100C**	**180**
Flow [lpm]	9.92	11.17	12.31
Stage 1	0.0171	0.0129	0.0107
Stage 2	0.0276	0.0244	0.0223
Stage 3	0.0563	0.0440	0.0367
Stage 4	0.0941	0.0800	0.0683
Stage 5	0.155	0.138	0.123
Stage 6	0.262	0.242	0.224
Stage 7	0.382	0.371	0.355
Stage 8	0.613	0.599	0.587
Stage 9	0.948	0.955	0.950
Stage 10	1.60	1.66	1.67
Stage 11	2.39	2.53	2.55
Stage 12	3.99	3.75	3.80
Stage 13	6.68	5.52	5.60
Stage 14	9.91	10.18	10.37

5 Temperature profile

Studies were conducted to measure the impactor internal temperature profile. Impactor heaters were set to 180 degrees C and the incoming sample was pre-heated to the same temperature. Thermocouples were placed inside the impactor into different positions to monitor the sample temperature inside the impactor. Results are presented in the following chart:

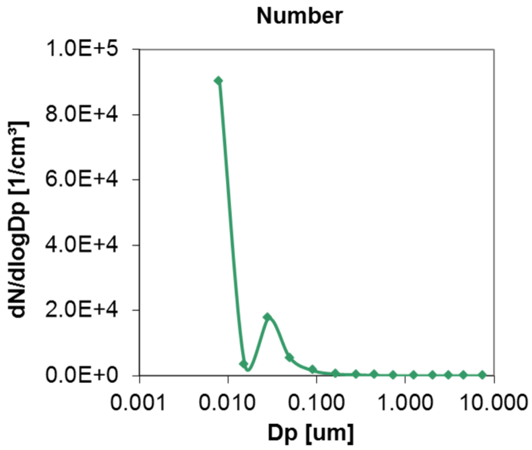


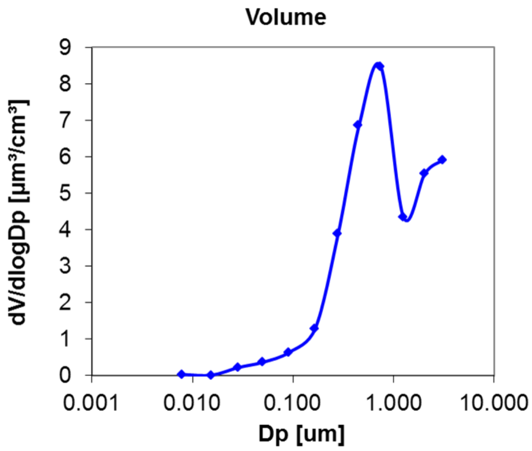


Starting from the room temperature impactor it takes approximately 4 hours until the temperatures are stabilized. Also due to heat losses and air gap between the impactor and its heater the impactor internal temperatures are slightly lower than the heater setpoint. However the actual impactor temperatures reach 150 degrees C which is enough to prevent condensation and nucleation in most cases.

6 Test measurements

Field tests have been performed with actual combustion aerosols at natural gas test bench at VTT. The High Temperature ELPI+ system was used to measure the particle size distributions inside the engine tailpipe, and that was further converted to both number and volume/mass weighted particle size distributions. Results are presented in the following charts:





Results were further compared to TSI SMPS system with a thermodenuder (for solid particles only) and to AVL SmartSampler for gravimetric measurement:

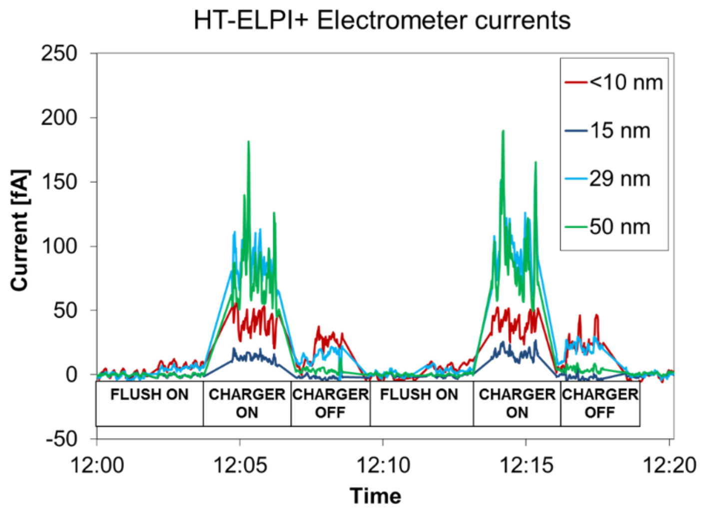
Number [#/cm3]	
HT-ELPI+	3.0e+4
SMPS With TD	2.7e6
Mass [mg/m3]	
HT-ELPI+ (dens=1)	0.0078
ISO 8178 (AVL SS)	7000

Comparison shows significant (two or three orders of magnitude) differences. However this is easily explained by aerosol dynamics and instrument specifications. Difference in number is caused by extremely small particle size, majority of the SMPS detected particles are in the 2-5 nm particle size range which is covered by the SMPS but not with the ELPI+. The difference in mass is caused by volatile material condensation; AVL SmartSampler does not prevent the VOC condensation like the High Temperature ELPI+

6.1 Combustion aerosol particle charging

An interesting and unique finding in the measurements was the hot aerosol charge measurement. In this measurement the ELPI+ charger is turned off and the electrometers are measuring the natural (net) charge of particles.

In the measurement sequence the first part was clean air (to check the electrometer offset levels), the next phase was a normal ELPI+ measurement with the ELPI+ charger and the last part was the ELPI+ current measurement without the charger:



The result indicates clearly that the signal caused by the smallest particles (sub-10 nm particles, red line) is almost unaffected by the ELPI+ charger, meaning that these particles are highly charged already in the tailpipe. This results has two important meanings:

1) It may indicate how the combustion particles are formed and
2) It may have a significant impact on the particle cleaning system and detection sensor (OBD sensor) operation

7 Conclusion

A new and unique measurement system was developed for combustion aerosol measurements at high temperatures. This allows particle size distribution and electrical net charge measurements without sample dilution, thus reflecting the actual situation inside the tailpipe. In addition to unique scientific possibilities offered by this system it also reduces the typical measurement system complexity a lot.