High Temperature Condensation Particle Counter (HT-CPC) A Novel Device for Nanoparticle Emission Measurement

Kanchit Rongchai and Nick Collings

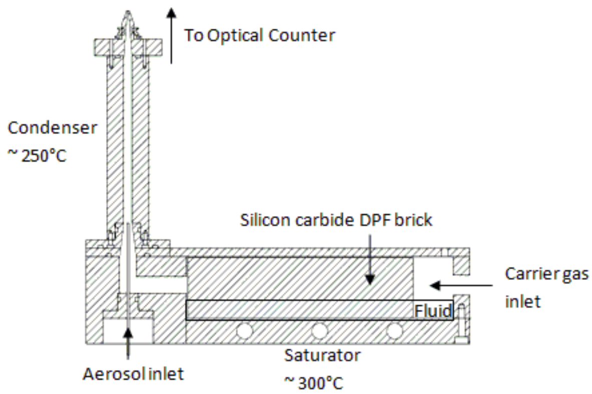
Department of Engineering, University of Cambridge
Trumpington Street, Cambridge CB2 1PZ, UK

In 2012, the World Health Organization classified diesel engine exhaust particles as carcinogenic to humans. Recent research suggests that the very smallest of these particles, the so-called nanoparticles, may be the most dangerous (1–3). The European Commission initiated the Particle Measurement Program (PMP) to develop new technologies for measuring particle number. It was decided that only solid particles should be measured for good repeatability and reproducibility, because volatile particles change rapidly in the atmosphere(4,5).

A typical butanol-based Condensation Particle Counter (CPC), which is limited to operate at around ambient temperatures, is used in the PMP protocol. The protocol requires a complex system to remove volatile material from the sample, which is done at high temperatures followed by cooling before it can be measured by the low temperature CPC.

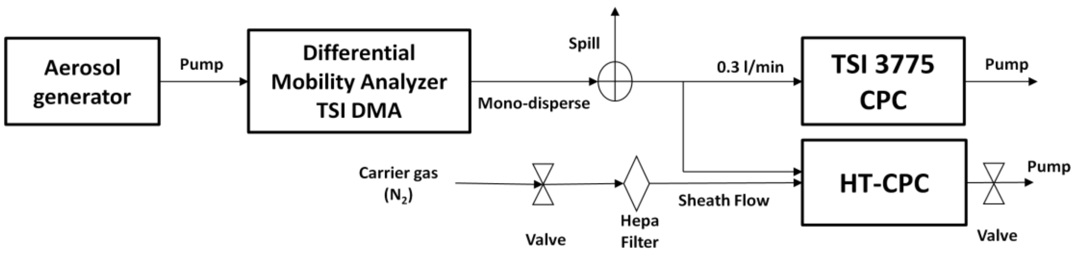
This work is concerned with the development of a novel high-temperature CPC (HT-CPC) as an alternative way of measuring solid particles. The aim is to design and build the HT-CPC that is by design insensitive to volatile particles, by operating at such a high temperature that volatile material is evaporated and cannot re-condensing. The HT-CPC will eliminate the need for cooling and problems associated with cooling. Moreover, it could replace the complex PMP system by a single device, and perhaps also of significance, be able to measure solid particles down to very small sizes if required.

Essential for the design process, a model of heat and mass transfer in the HT-CPC, similar to (6), was constructed. The model allowed key parameters such as Kelvin-equivalent counting efficiency, volatile evaporation and homogeneous nucleation to be predicted. The simulations suggested that the HT-CPC will be able to grow and detect solid nanoparticles. A prototype was then constructed accordingly.



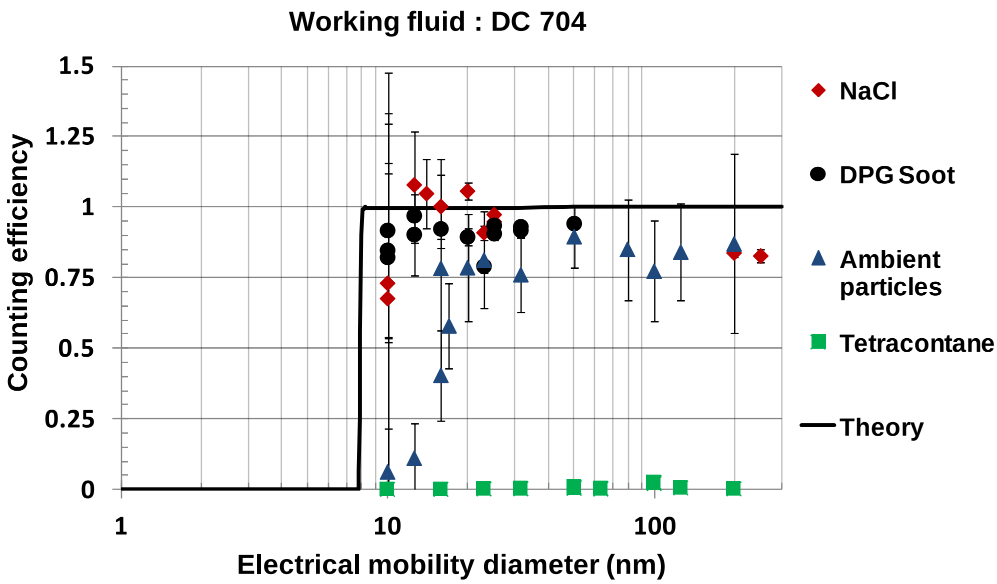
One crucial design criterion was selection of high-temperature working fluids. The short listed candidates including organic oils (DEHS), perfluorocarbons (e.g. Fomblin fluids), silicone fluids (Dow Corning 704, 705 or equivalents) and poly-phenylethers (e.g. Santovac 5) were tested experimentally.

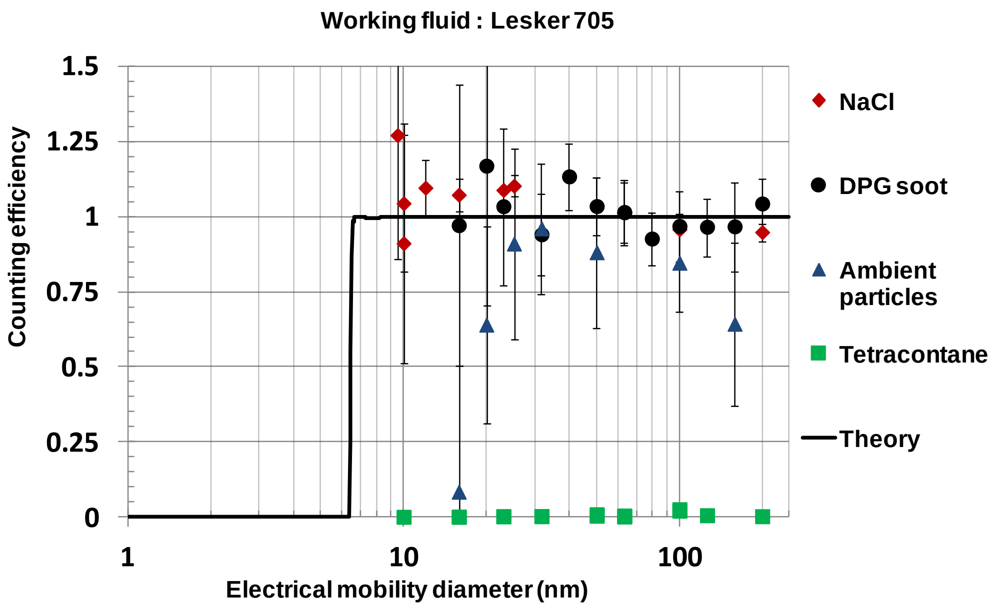
The experimental set-up, comprised an aerosol generator, a differential mobility Analyzer (DMA), a TSI 3775 low-temp Butanol CPC and the HT-CPC. Test aerosols used in the experiments were NaCl, combustion-generated particles (generated from a Cambustion DPG), lab ambient particles and volatile tetracontane particles.



Results

Without sample pre-heating or dilution, the HT-CPC using DC704 or Lesker705 fluids was able to grow and detect solid particles as predicted by the model. It successfully removed volatile tetracontane particles of electrical mobility diameter range 7nm to 310nm at concentration > 10^4 particles/cc with ≥ 99% efficiency as required by the European Commission's PMP. Lesker705 allowed the HT-CPC to operate stably at 290°C, the highest temperature ever achieved of its kind in history so far.





Conclusion

The HT-CPC was successfully built and tested. Using 704 and 705 silicone fluids, the HT-CPC could detect NaCl and soot particles as predicted by theory. It was able to remove tetracontane volatile particles up to 99% efficiency. The HT-CPC allows solid particles to be measured using just a single device.

Reference

1. Ristovski Z, Miljevic B, Surawski N, Morawska L, Fong K, Goh F. Respiratory health effects of diesel particulate matter. Respirology. 2012;17:201–12.

2. Hofmann W. Modelling inhaled particle deposition in the human lung—A review. Journal of Aerosol Science. Elsevier; 2011;42(10):693–724.

3. International Commission on Radiological Protection. Human respiratory tract model for radiological protection: A report of a task group of the International Commission on Radiological Protection. ICRP Publication 66. Annals of the ICRP. 1994;24(1-3):36–54.

4. Giechaskiel B, Chirico R, Decarlo PF, Clairotte M, Adam T, Martini G, et al. Evaluation of the particle measurement programme (PMP) protocol to remove the vehicles' exhaust aerosol volatile phase. The Science of the total environment. Elsevier B.V.; 2010;408(21):5106–16.

5. AEA Energy & Environment. Report to the Department for Transport: Volatile Particle Remover Calibration and Validation Procedures. UNECE. 2007 p. 6.

6. Stolzenburg MR, McMurry PH. An Ultrafine Aerosol Condensation Nucleus Counter. Aerosol Science and Technology. 1991;14(1):48–65.

17th ETH Conference on Combustion Generated Nanoparticles

23rd – 26th June 2013
ETH Zentrum, Zürich

High Temperature Condensation Particle Counter (HT-CPC)
A Novel Device for Nanoparticle Emission Measurement

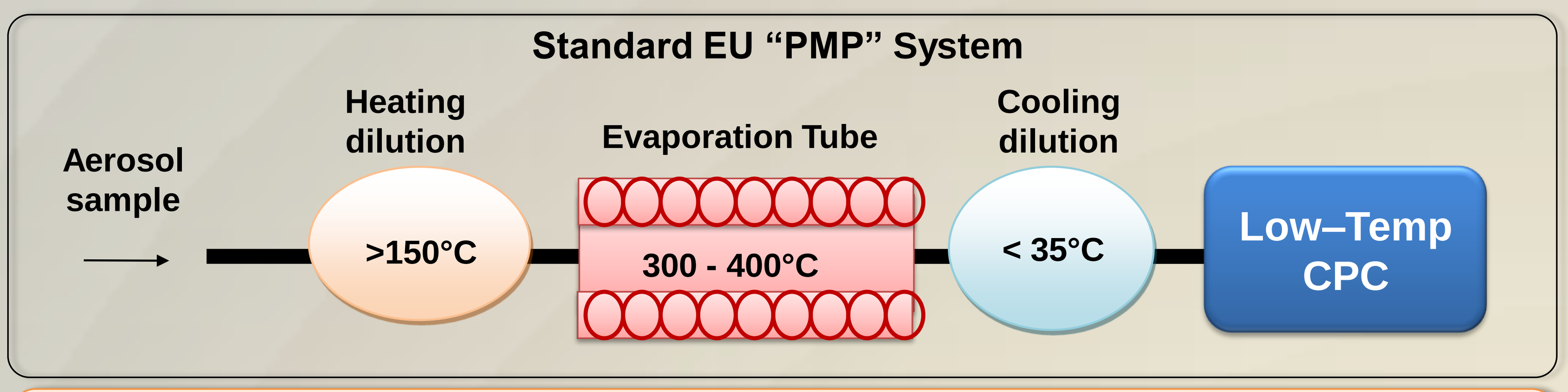
Kanchit Rongchai and Nick Collings

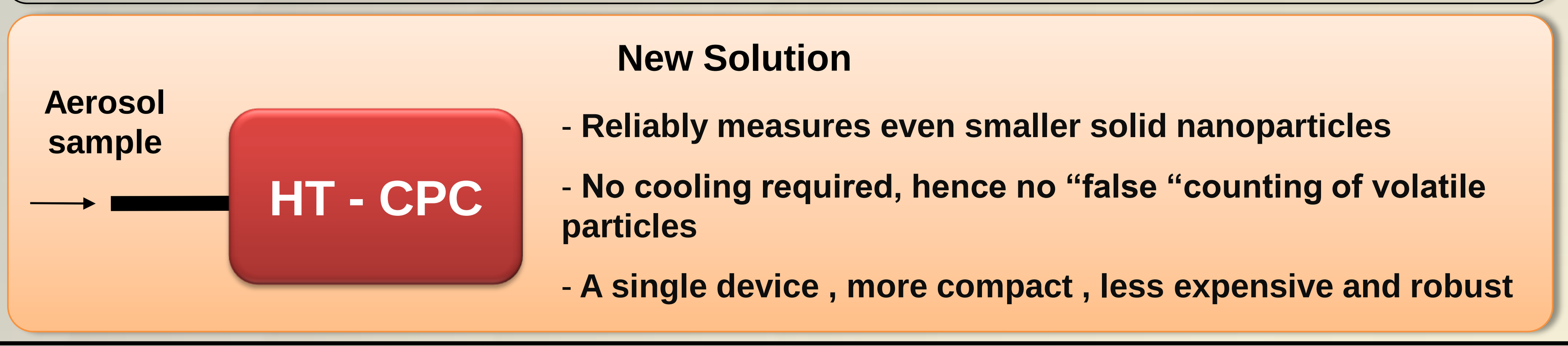
Department of Engineering , University of Cambridge

UNIVERSITY OF CAMBRIDGE
DEPARTMENT OF ENGINEERING

About our work

We have designed, built and successfully tested a novel device called the *High-Temperature Condensation Particle Counter (HT-CPC)*, a new solution to the problem of measuring vehicle particle emission numbers which are now regulated by EU law. The "standard" technique for such measurements, consists of a complex and expensive system, and is possibly not fit for purpose[1]. Our HT-CPC could replace this complex system with a single and relatively inexpensive device. The aim was to design and build a device that by design, only measures solid (as opposed to liquid particles) in the spirit of the relevant EU legislation. This is achieved by operating at such a high temperature that liquid particles evaporate and cannot re-condense. In this way, the HT-CPC eliminates the need for a complex sample pre-conditioning system. It is also sensitive to very small solid nanoparticles if required.





Motivations

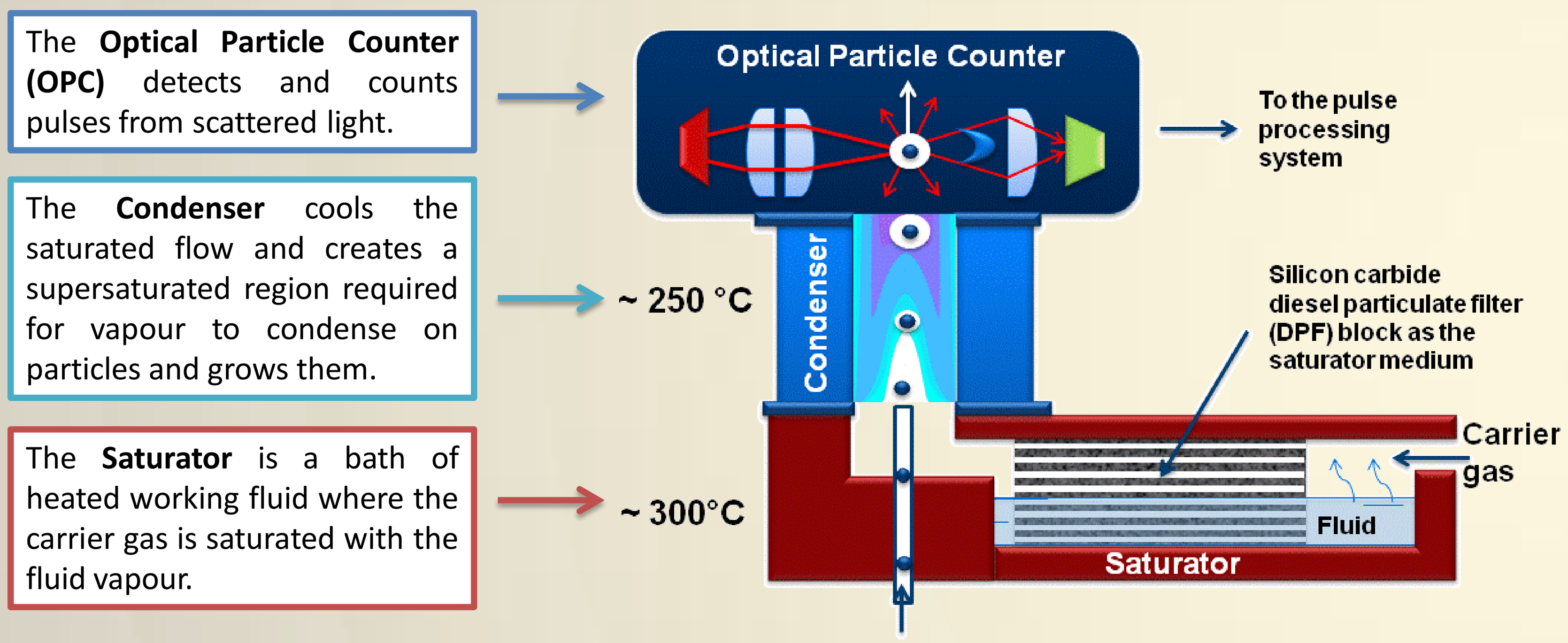
Our research is directly motivated by the impact of anthropogenic particle emissions on health, climate and environment. Many cities around the world have an air pollution problem. The World Health Organization has recently listed diesel engine exhaust particles as carcinogenic to humans. Recent research suggests that instead of large particles, the very smallest of these particles, the so-called nanoparticles, may be the most dangerous[2,3]. Therefore, accurate measurement of these particles is key to tackling the problem.

With this in mind, the European Commission initiated the Particle Measurement Program (PMP) to develop new technologies for measuring the number of small particles in engine exhaust. To ensure that measurement can be reliably reproduced, the PMP protocol states that only solid particles should be measured, because volatile particles change rapidly in the atmosphere[4], and that only particles larger than 23nm diameter should be counted.

However, there are challenges in the operation of the PMP protocol. It requires a complex system to remove volatile material from the sample, which is done at high temperatures followed by cooling before it can be measured by a low-temperature Condensation Particle Counter (CPC). In some cases, the cooling also introduces problems with artefact volatile particles and complications but this is currently inevitable with the low-temperature CPC. Our research aims to provide a new tool that could be used to improve public health, the environment and climate, both locally and globally.

How the HT-CPC Works

Like typical low-temp Condensate Particle Counters (CPCs), the HT-CPC "grows" nanoparticles by condensing on to them a special kind of fluid until they grow large enough to be detected by light scattering. While Butanol is commonly used as a working fluid in low-temp CPCs, the HT-CPC uses a very high-temperature fluid.



Since the HT-CPC operates at high temperatures, it automatically removes all liquid particles, so that only the stable, solid, ones are measured. This makes the measurement of nanoparticles more reliable.

Design of the HT-CPC

We constructed a theoretical model of heat and mass transfer and Kelvin-equivalent diameter in the condenser of the HT-CPC which allowed us to predict the particle size-dependent counting efficiency. The model also allowed other key parameters such as, geometry of the HT-CPC, volatile evaporation and homogeneous nucleation (fault counts) to be predicted.

How hot should it be?

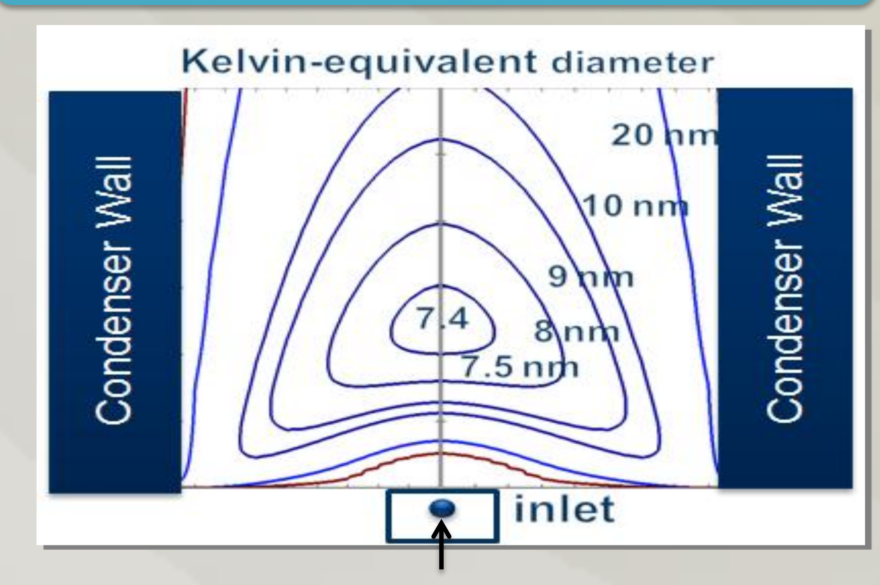
Analysis on the evaporation of tetracontane particles (representing volatile combustion particles), we found that the HT-CPC should be > 150°C.

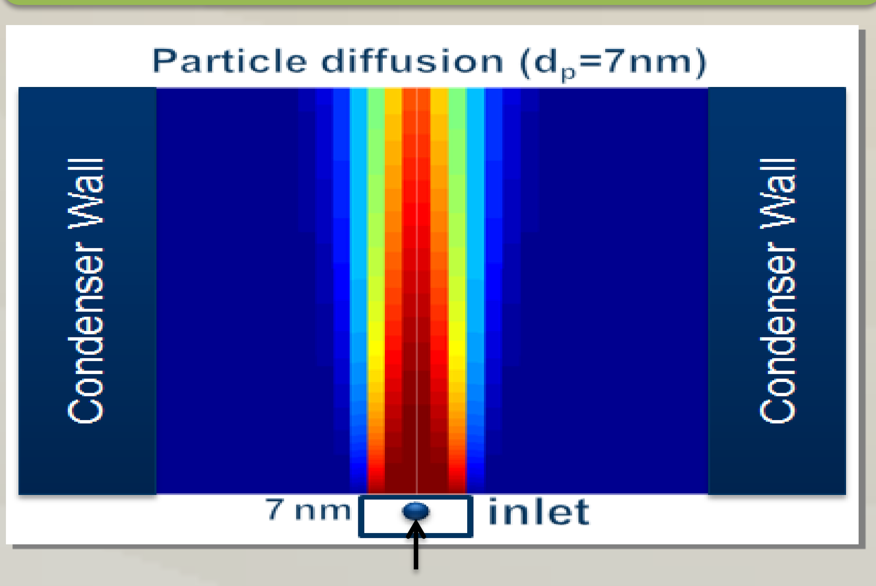
Selection of working fluids

Our model enabled us to specify the properties of an ideal working fluid. Shortlisted fluids were organic oils (DEHS), Perfluoro-carbon (Fomblin Y), polyphenyl-ether (Santovac 5), and silicone fluids (DC704 and Lesker705).

Properties of an ideal working fluid

- Non-toxic, chemically inert, stable at high temperatures, widely available and cost-effective
- High boiling point
- Mass diffusivity < the thermal diffusivity of the carrier gas to achieve supersaturation required for particle growth activation.
- It should be able to 'wet' particles.
- Vapour pressure sufficient to grow particles to detectable sizes.

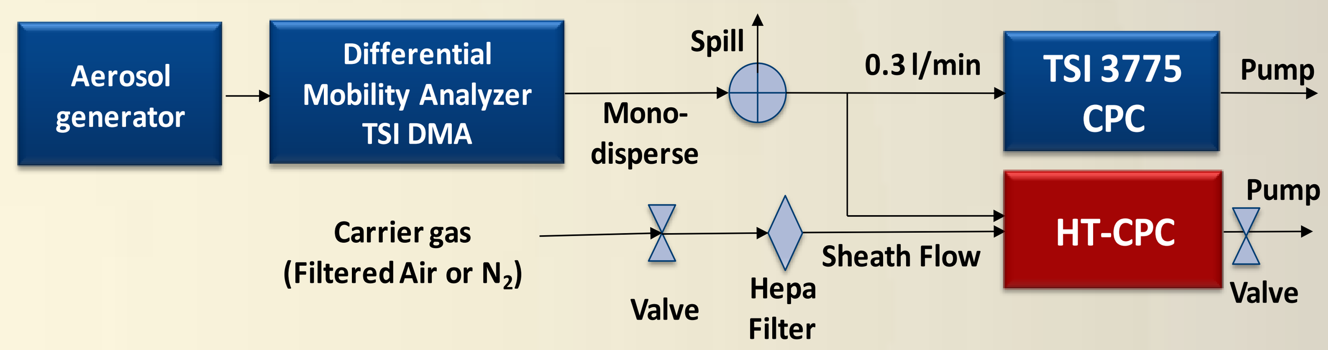




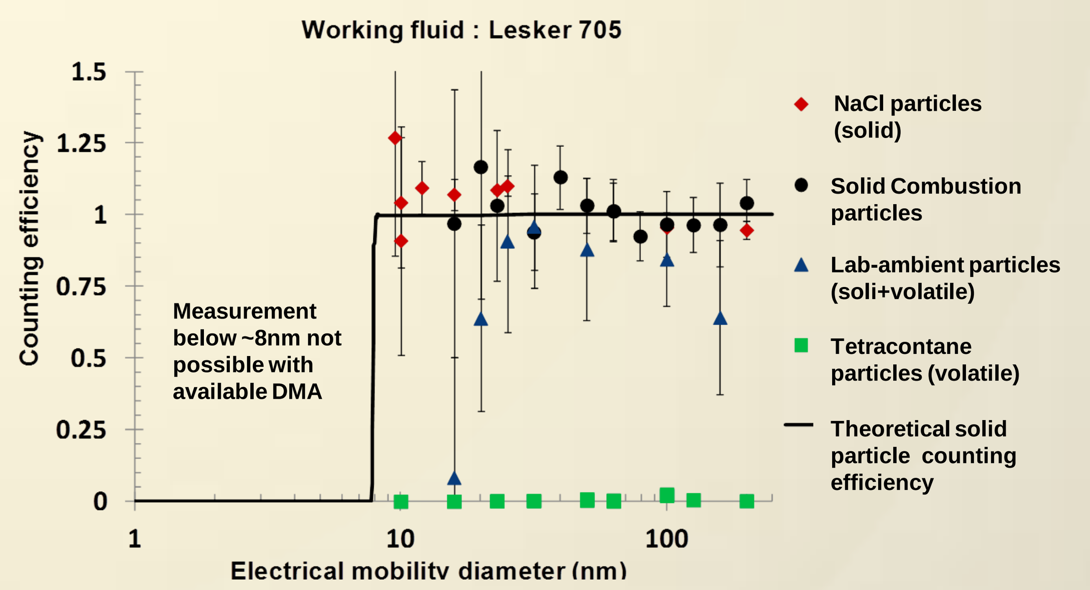
The model suggested that the HT-CPC will be able to grow and detect solid nanoparticles and remove tetracontane volatile particles at the same time. A prototype was then designed and built based on the model simulations.

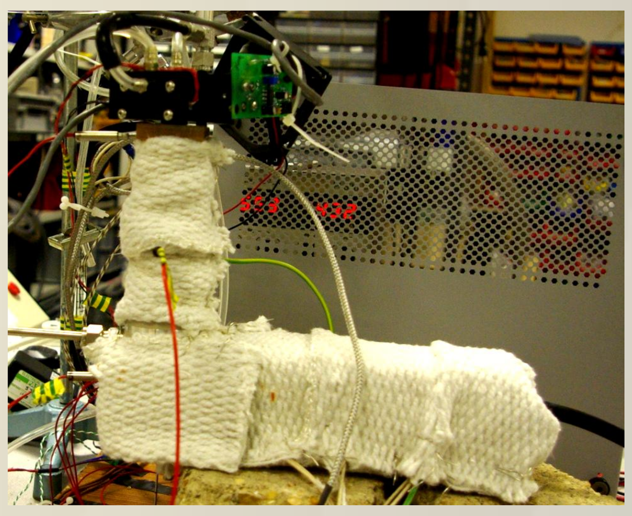
Testing and Performance of the HT-CPC

The experimental set-up comprised an aerosol generator, a differential mobility analyzer (DMA), a TSI 3775 low-temp Butanol CPC and the HT-CPC. Test aerosols used in the experiments were NaCl, combustion-generated solid particles (generated from a Cambustion DPG™), lab ambient particles and volatile tetracontane particles.



The HT-CPC and TSI CPC were compared and the counting efficiency as a function of particle electrical mobility diameter was obtained.





The HT-CPC in operation

- Without sample pre-heating or dilution, the HT-CPC using DC704 or Lesker705 fluids was able to grow and detect solid particles as predicted by the model.
- It successfully removed volatile tetracontane particles of electrical mobility diameter range 7nm to 310nm at concentration > 10^4 particles/cc with ≥ 99% efficiency as required by the European Commission's PMP.
- Lesker705 allowed the HT-CPC to operate stably at 290°C, the highest temperature ever achieved of its kind in history so far (typically only 35°C).

Conclusions

We have provided a novel solution, the High Temperature Condensation Particle Counter (HT-CPC), for reliable measurement of solid nanoparticle emissions, as desired by the relevant EU legislation. It operates at such a high temperature that all liquid particles automatically disappear.

The HT-CPC eliminates the need for complicated pre-conditioning stages and allows very small solid nanoparticles to be measured using a single, inexpensive device.

The HT-CPC has significant and serious commercial application. Diesel particles have recently been confirmed as carcinogenic, and more practical, reliable methods for measuring them are urgently required. Unlike the measurement of gaseous pollutants (e.g. NOx and carbon monoxide), particle measurement is much more challenging. If reliable methods of measurement are not forthcoming, important legislation concerning particle emissions may be difficult to be fully effective.

[1] UNECE, 2010, Uniform Provisions Concerning the Approval of Vehicles with Regard to the Emission of Pollutants According to Engine Fuel Requirements (83).
[2] Ristovski Z. O. D., Miljevic B. R., Surawski N. I. C., Morawska L. I., Fong K. W. U. N. M., Goh F. E., and Yang I. A. N. A., 2012, "Respiratory health effects of diesel particulate matter," Respirology, 17, pp. 201–212.
[3] Hofmann W., 2011, "Modelling inhaled particle deposition in the human lung—A review," Journal of Aerosol Science, 42(10), pp. 693–724.
[4] Kittelson D. B., 1998, "Engines and Nanoparticles: A Review," Journal of Aerosol Science, 29(5), pp. 575–588.

Contact: Engineering Department, Trumpington Street, Cambridge CB2 1PZ email: kanchit.rongchai@gmail.com, nc10001@cam.ac.uk