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Analyses of ambient aerosol size distribution using optical particle counter

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PARTICLES
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1. What is OPC?
2. What is coincidence loss?
3. Objective of present work
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Optical Particle Counter (OPC)

OPC can measure the size distribution and number concentration of **0.3～10 μm particles in situ and in real time.** ⇒ Essential data for particle behavior so as to devise effective removal devices

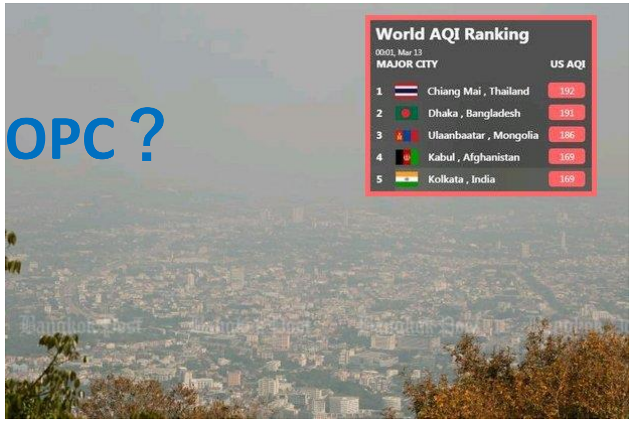
Cleanroom Particle Counter

Problem

OPC cannot measure high concentration aerosols because it detects scattered light form single particles

Can we trust OPC？

In Delhi, air pollution

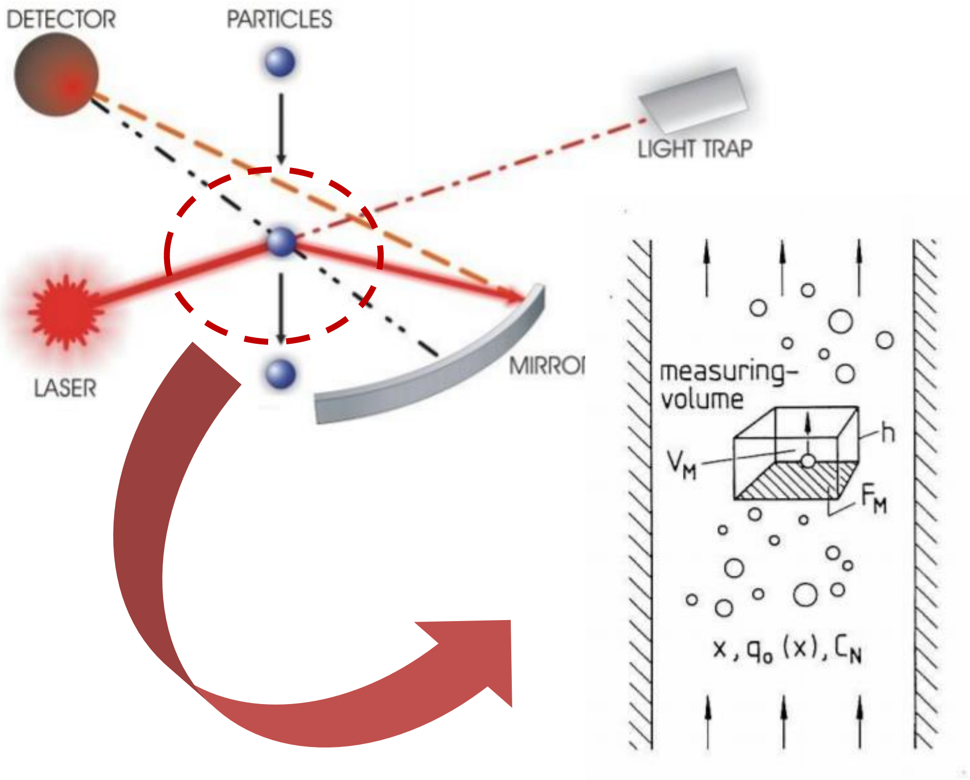


Doi Suthep and the world air-quality index at midnight on March 13, 2019

Application of OPC to high concentration aerosol

PP8306 *Measurable size range:* 0.3 – 25 µm

Meets ISO 21501-4 and JIS B9921



Can we use OPC?

Human coughing

Smoke from cigarette

Burning of incense

Objective

Clarify the influence of coincidence on OPC measurement results under condition of high concentration aerosols

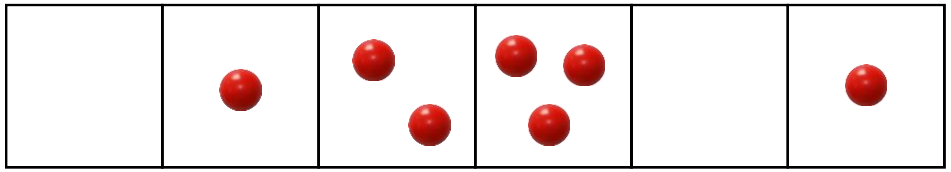
Proper usage of OPC for high concentration aerosols

Coincidence loss for high concentration aerosol

Poisson Distribution

P_n = Probability of n particles present in a view volume

$$P_n = e^{-\lambda}\frac{\lambda^n}{n!}$$



λ = The expected number of particles in the view volume $= \sum nP_n = N_t Q_s t_d$

For n = 0 $\quad P_0 = e^{-\lambda}$

$N_i =$ Number concentration measured by OPC
N_t = True number concentration
Q_s = Sampling flowrate
t_d = Dead time

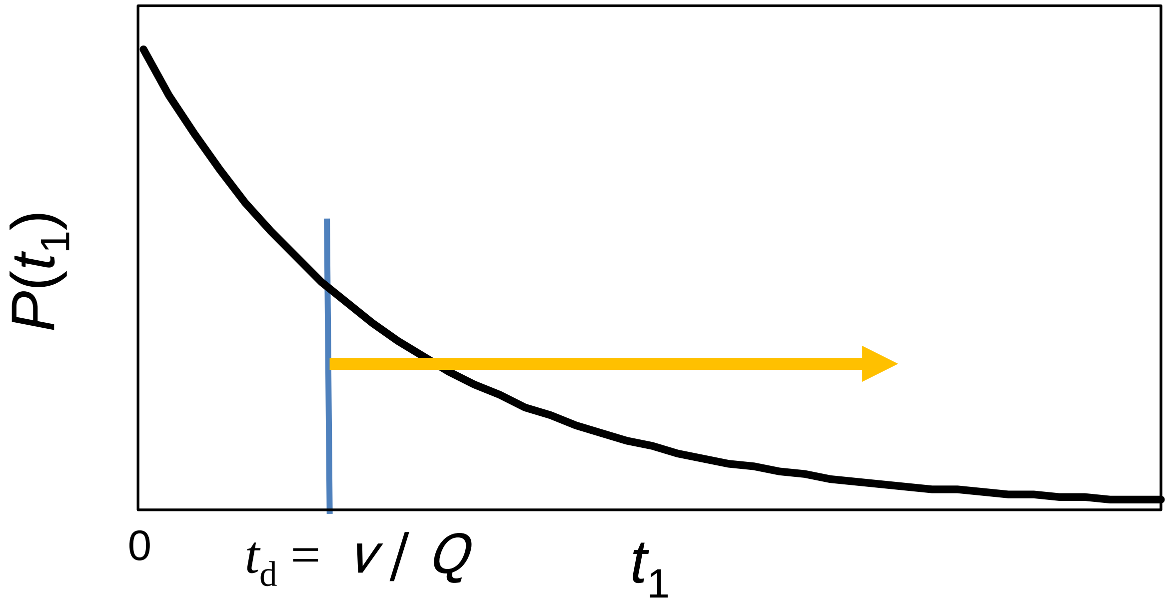
$$\frac{N_i}{N_t} = \frac{P_1+P_2+P_3+\cdots+P_n}{\sum nP_n} = \frac{1-P_0}{\lambda} = \frac{1-e^{-\lambda}}{\lambda} = \frac{1-e^{-N_t Q_s t_d}}{N_t Q_s t_d}$$

Coincidence loss for high concentration aerosol

Erlang Distribution

$P(t_k)$= Arrival time distribution of k-th particle to view volume

$$P(t_k) = \frac{\alpha^k}{(k-1)!} {t_k}^{k-1} e^{-\alpha t_k}$$



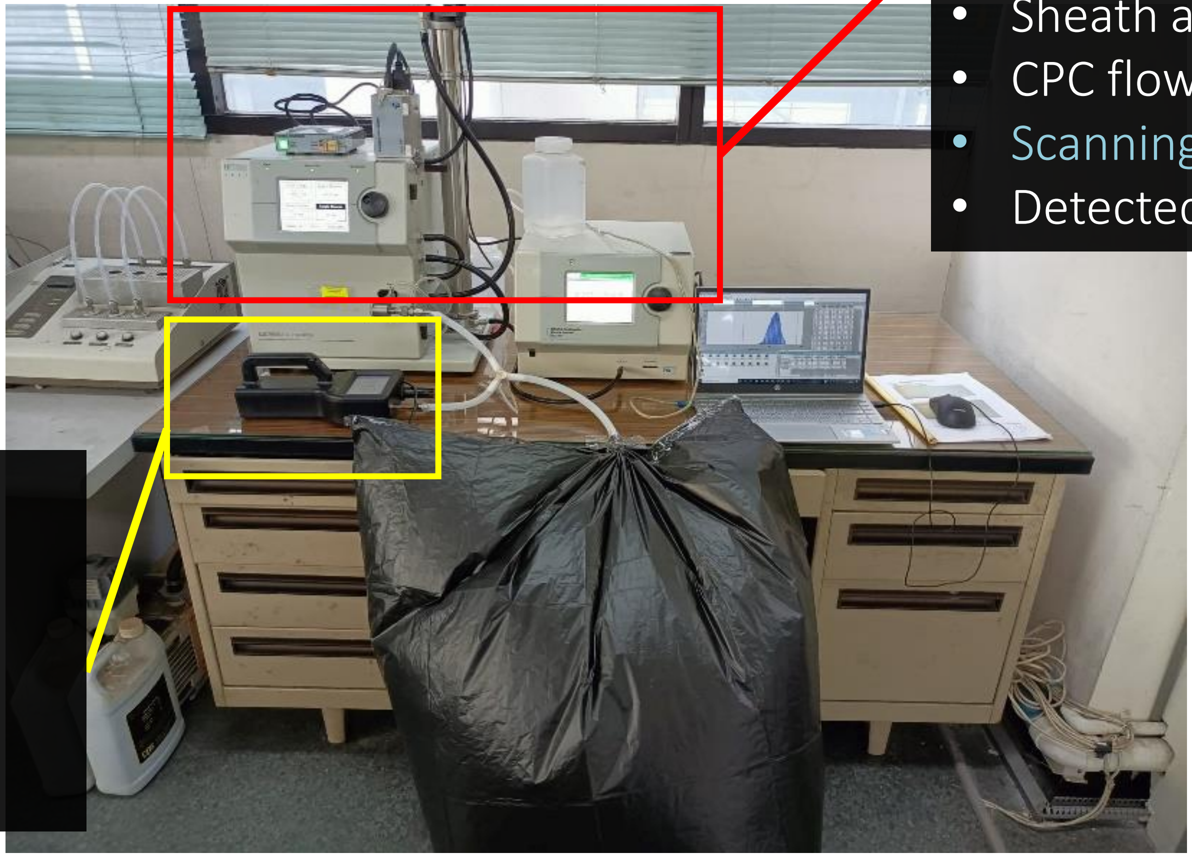
OPC can count particles with t_1 longer than dead time t_d

$$\frac{N_i}{N_t} = \int_{t_d}^{\infty} P(t_1) dt_1 = e^{-\alpha t_d} = e^{-\lambda} = e^{-N_t Q_s t_d}$$

λ = Expected number of particles in the view volume $= N_t Q_s t_d$

Calibration of OPC with SMPS

Incense smoke



SMPS setting

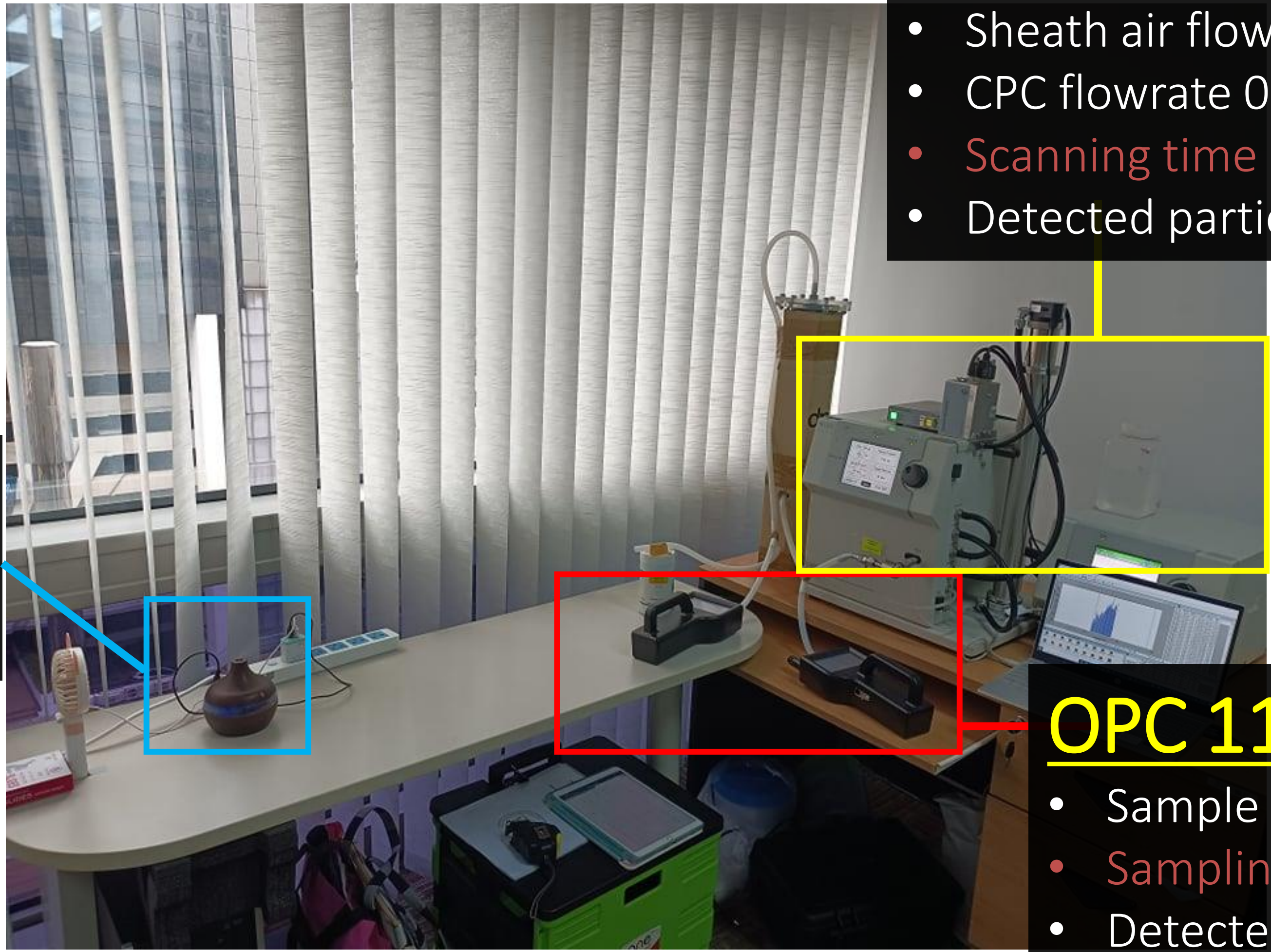
- Aerosol flowrate (DMA) 0.3 LPM
- Sheath air flowrate (DMA) 3 LPM
- CPC flowrate 0.3 LPM
- Scanning time 2 min
- Detected particle size 0.014-0.662 µm

OPC 117 setting

- Sample flowrate 2.83 LPM
- Sampling time 2 min
- Detected particle size 0.3-25 µm

Humidifier

Aqueous NaCl in water solution (0, 0.01, 0.5wt% NaCl)



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OPC 117 setting

- Sample flowrate 2.83 LPM
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Saline droplets and NaCl particles

Saline solution
(0.01, 0.5wt% NaCl)

Humidifier

Saline droplets

Diffusion dryer

SMPS setting

- Aerosol flowrate (DMA) 0.3 LPM
- Sheath air flowrate (DMA) 3 LPM
- CPC flowrate 0.3 LPM
- Scanning time 2 min
- Detectable size range
  0.014-0.662 µm

SMPS

NaCl particles

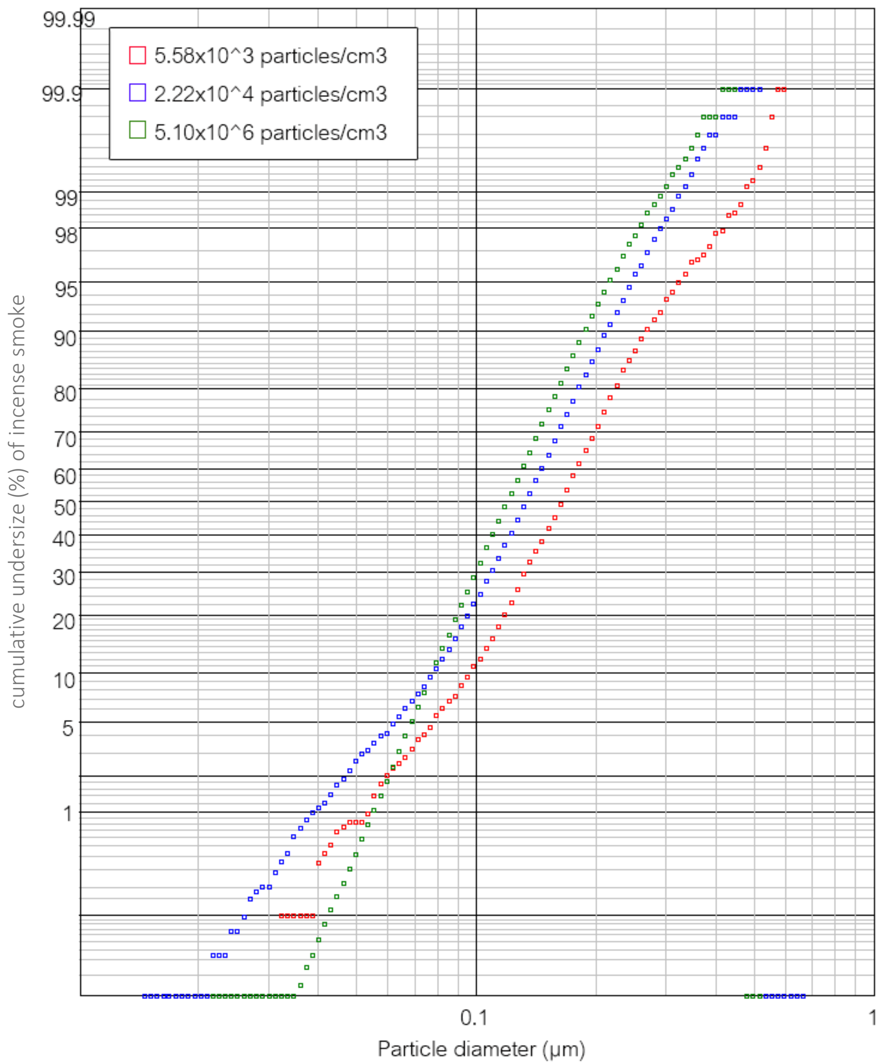
OPC Upstream

OPC setting

- Sampling flowrate 2.83 LPM
- Sampling time 2 min
- Detectable size range
  0.3-25 µm

OPC Downstream

Test aerosol – Incense smoke



Lognormal probability plot of incense smoke measured by SMPS at different sampling concentration

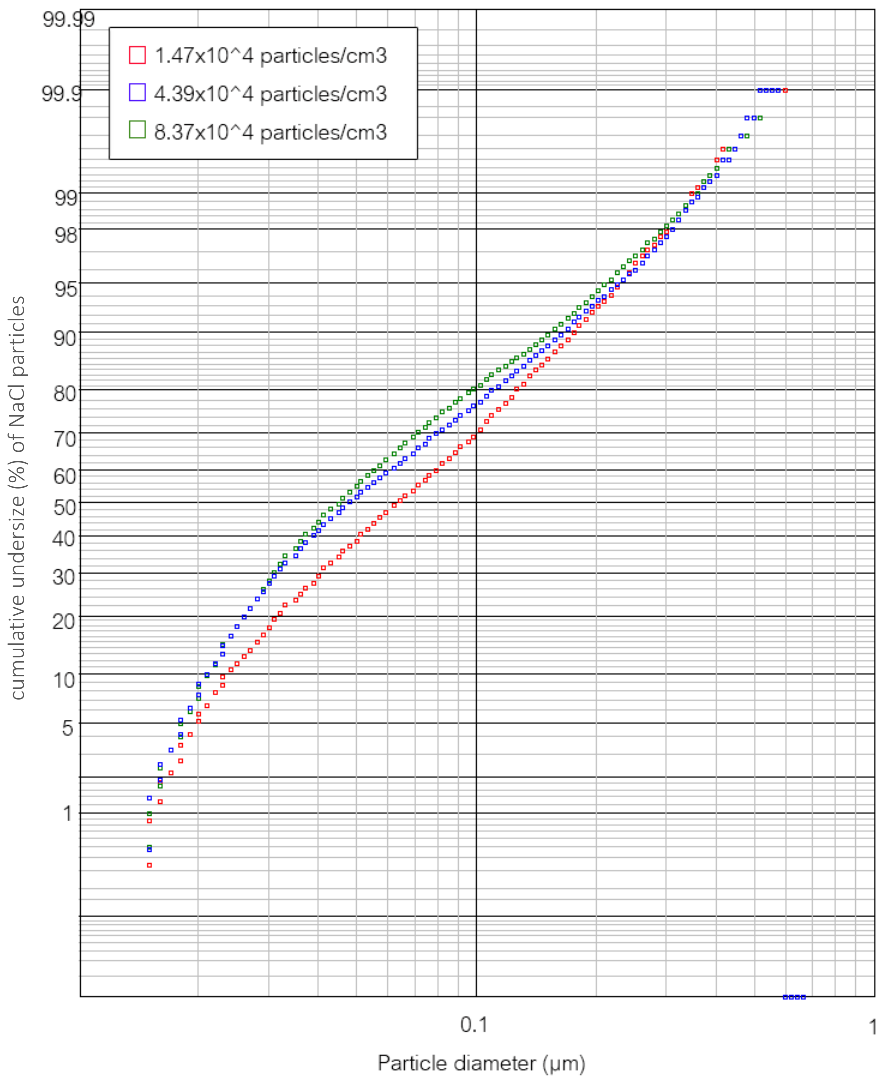
The geometric mean particle diameter and the geometric standard deviation of incense smoke measured by SMPS

Total concentration (particles/cm^3)	D_{p50} (μm)	σ
5.58×10^3	0.162	1.44
2.22×10^4	0.131	1.49
5.10×10^6	0.117	1.43

*D_{p50} = The geometric mean particle diameter
σ = The geometric standard deviation

- The change of concentration changed PSD.
- Higher concentration provided smaller geometric mean particle diameter.
- At the highest concentration, the number concentration of small particles decreased due to the loss from diffusion.

Test aerosol – Solid NaCl particles



Lognormal probability plot of NaCl particles from 0.01wt%NaCl solution measured from SMPS at different sampling concentration

The geometric mean particle diameter and the geometric standard deviation of NaCl particles after dried from 0.01wt%NaCl solution measured by SMPS

Total concentration (particles/cm^3)	D_{p50} (μm)	σ
1.47×10^4	0.070	2.24
4.39×10^4	0.048	2.62
8.37×10^4	0.045	2.51

*D_{p50} = The geometric mean particle diameter
σ = The geometric standard deviation

- The change of concentration changed PSD.
- Higher concentration provided smaller geometric mean particle diameter.

Test aerosol – Saline droplets

NaCl particle diameter converting to Saline droplet diameter

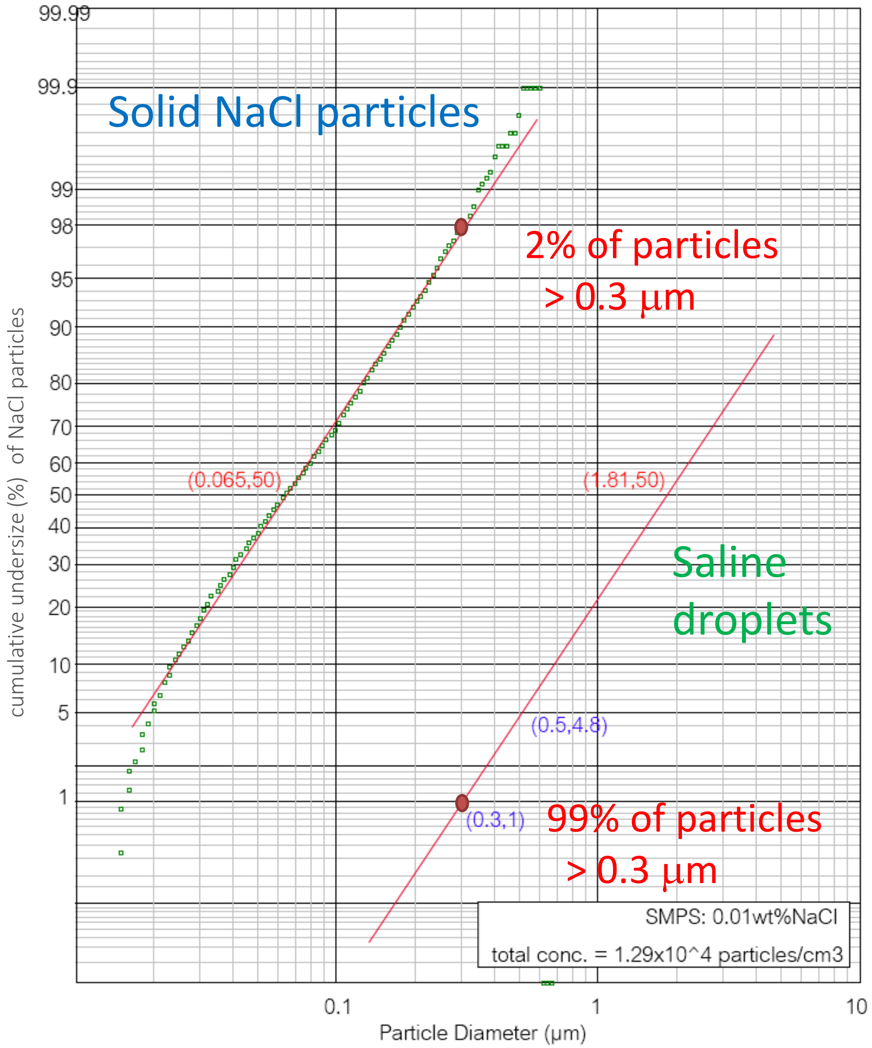
Mass balance (on an assumption 100% dry of saline droplets)

$$(wt\%NaCl)\rho_{Sol}\left(\frac{\pi d_d{}^3}{6}\right) = \rho_{NaCl}\left(\frac{\pi d_p{}^3}{6}\right)$$

$wt\%NaCl$ = weight percentage of NaCl in water
ρ_{Sol} = density of NaCl solution ≈ density of water (kg/m^3)
d_d = diameter of saline droplet (m) – conversion diameter
ρ_{NaCl} = density of NaCl particle (kg/m^3)
d_p = diameter of NaCl particle obtained from SMPS (m)

$$C_{0.3-0.5} = (\%Cum_{0.5} - \%Cum_{0.3})C_t$$

$C_{0.3-0.5}$= the number concentration of saline droplets (particles/cm^3) of particles at diameter in the range of 0.3 - 0.5 µm
$\%Cum_{0.3}, \%Cum_{0.5}$ = percentage cumulative concentration of saline droplets at diameter in the range of 0.3 and 0.5 µm
C_t= total number concentration of saline droplets (particles/cm^3)



Lognormal probability plot of NaCl particles from 0.01wt%NaCl solution measured by SMPS

Test aerosols

- Incense smoke
- NaCl particles

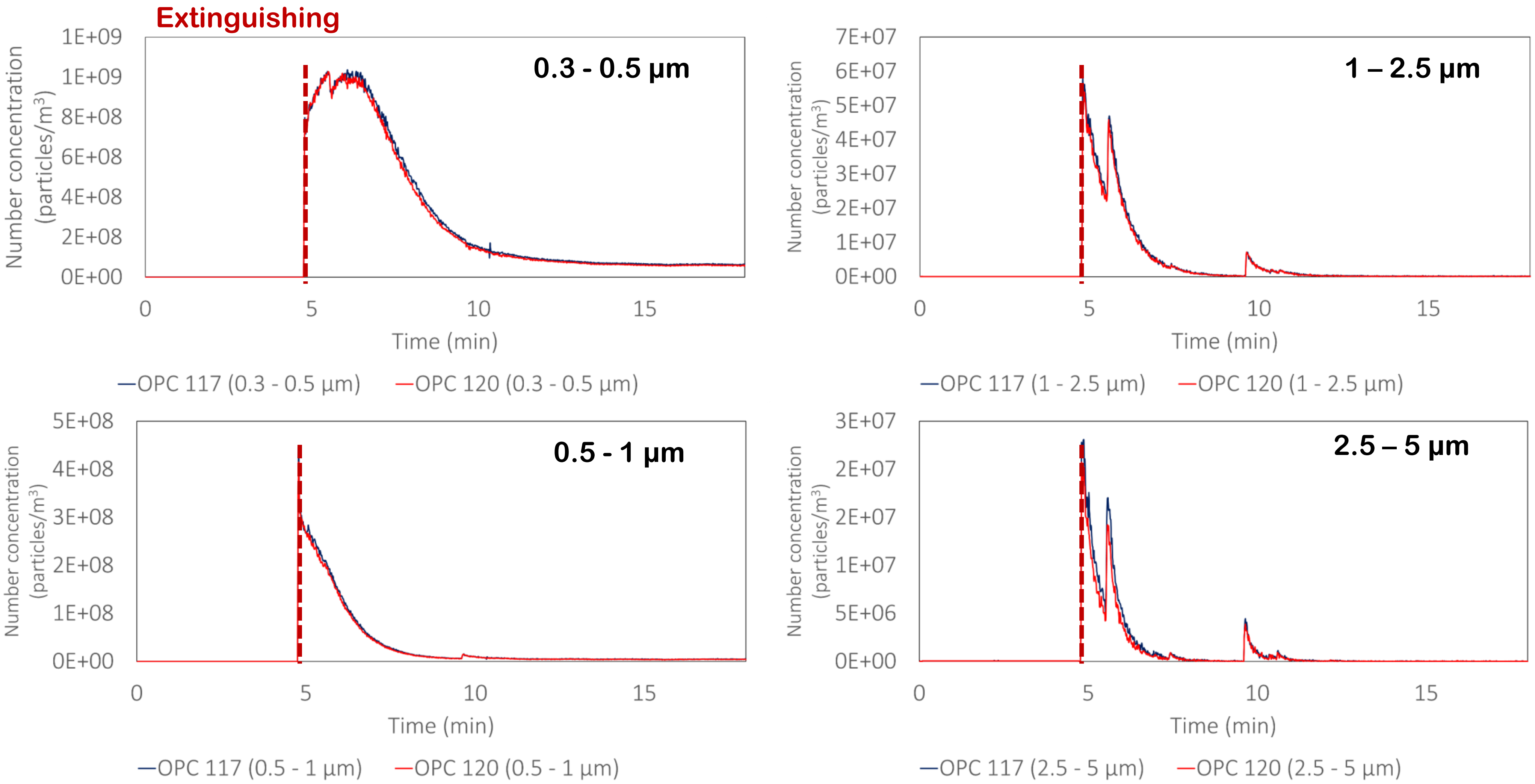
Materials	D_{p50} (µm)	σ_g
Incense smoke	0.15	1.45
NaCl particles (0.01 wt%)	0.05	2.46
NaCl particles (0.5 wt%)	0.07	2.31

- Saline droplets

Materials	D_{p50} (µm)	σ_g
Saline droplets (0.01 wt%)	1.71	2.17
Saline droplets (0.5 wt%)	0.53	2.24

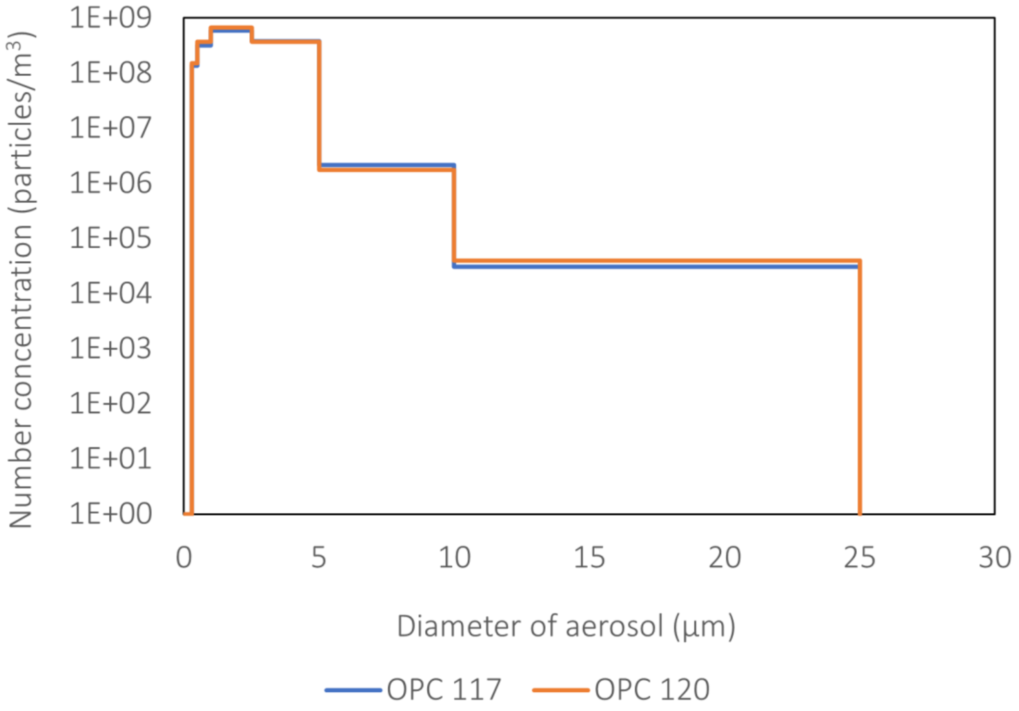
*D_{p50} = The geometric mean particle diameter
σ = The geometric standard deviation

Comparison of 2 OPCs to incense smoke



Responses of OPCs are consistent even over the measurement range of concentration.

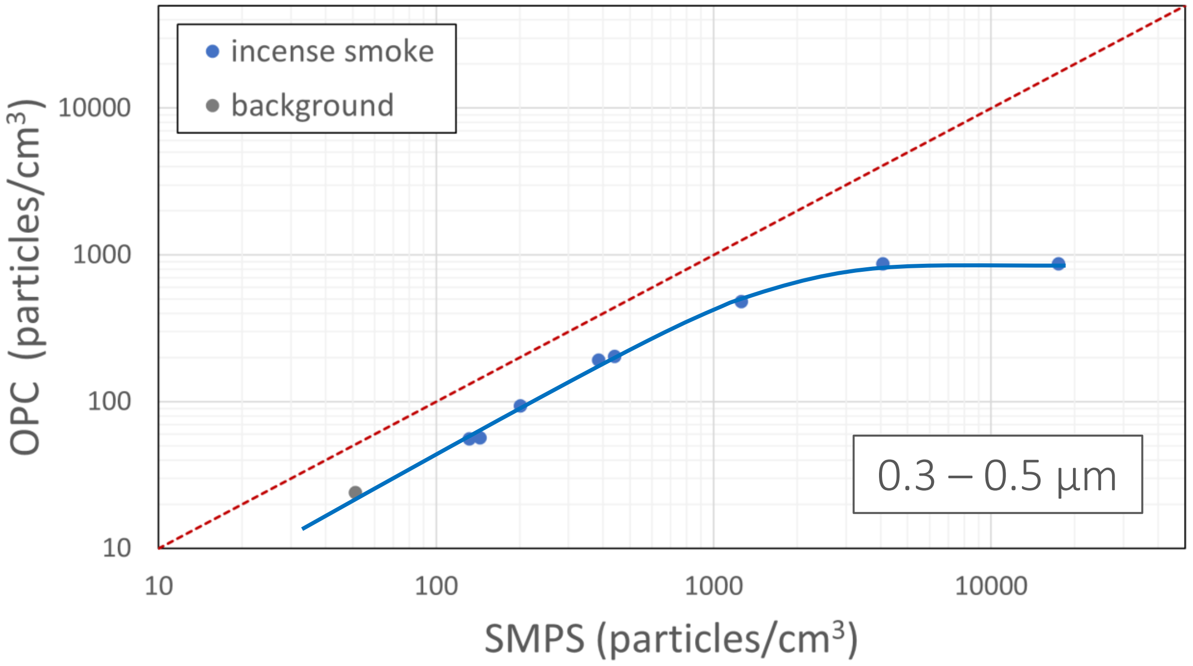
Saline concentration (1.0 wt% NaCl)



Particle size (µm)	Number concentration of particles (particles/m^3)	
	OPC 117	OPC 120
0.3 – 0.5	136,940,403	152,721,542
0.5 – 1.0	315,630,086	367,397,133
1.0 – 2.5	594,697,088	664,882,982
2.5 – 5.0	377,058,214	368,534,496
5.0 – 10.0	2,146,414	1,765,961
10.0 – 25.0	31,005	39,976
Total	1,426,503,210	1,555,342,091

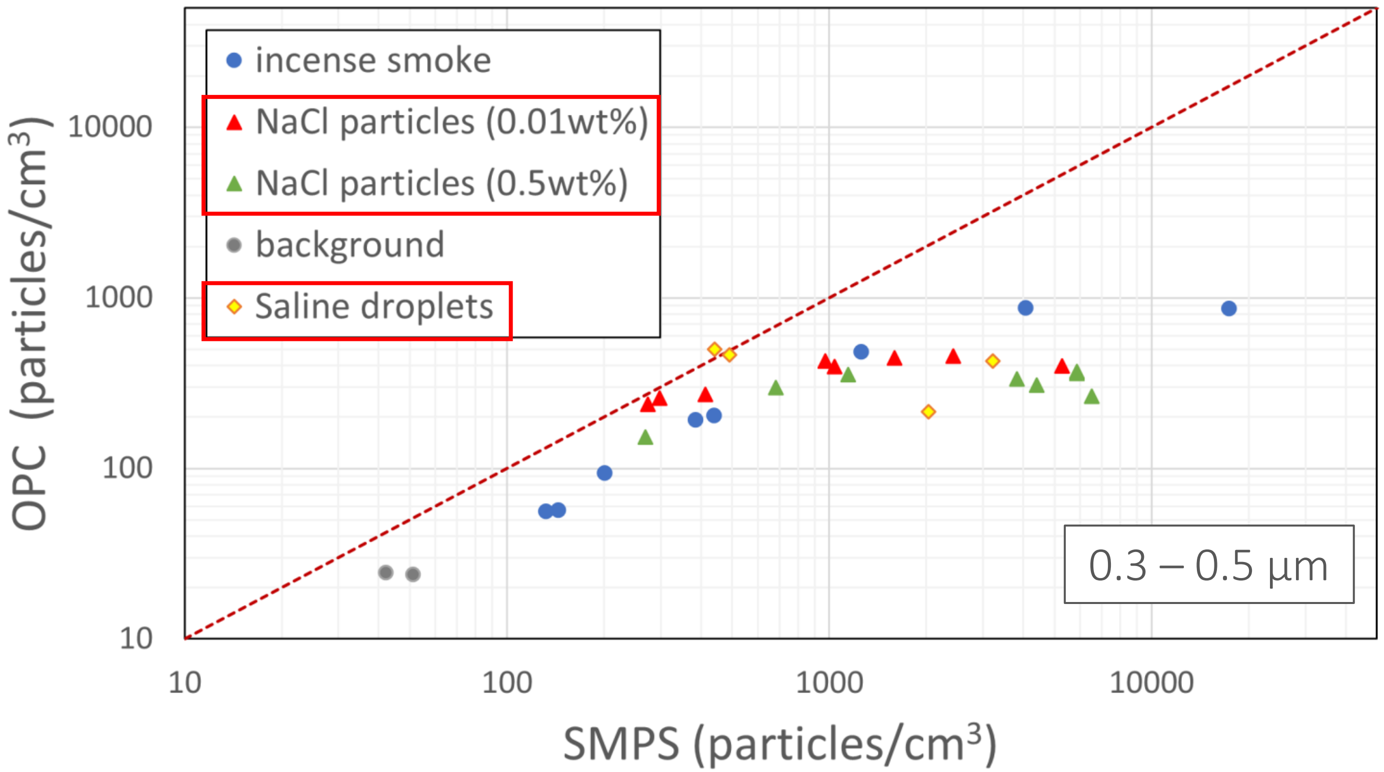
Responses of OPCs are consistent even over the measurement range of concentration.

Incense smoke



- The number concentration of incense smoke measured by OPC linearly increases with that measured by SMPS .
- The curve reaches a plateau at 1000 particles/cm^3.
- The number concentrations measured by OPC are about a half of those measured by SMPS because incense smoke is opaque.

Saline droplets and NaCl particles



10% coincidence loss concentration specified by the manufacturer is 1000 cm^{-3}.

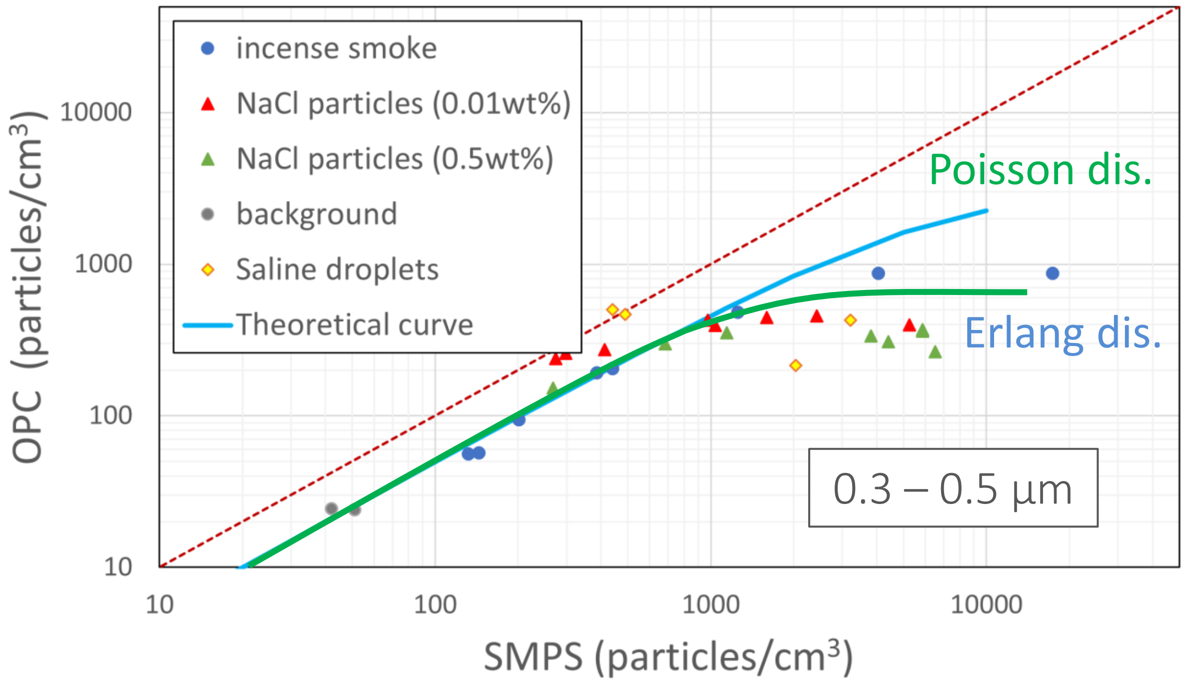
NaCl particles and saline droplets data are not much different from the incense smoke data

For incense smoke in which there are many particles smaller than the detection limit of OPC, and for saline droplets with the number median size of 2 µm, when 0.3-0.5 µm number concentration measured by the OPC does not exceed the 10% coincidence loss concentration specified by the manufacturer, we can measure the concentration by OPC.

Coincidence loss based on Poisson distribution

$$\frac{N_i}{N_t} = \frac{1 - e^{-N_t Q_s t_d}}{N_t Q_s t_d}$$

N_i = Number concentration measured by OPC
N_t = Number concentration measured by SMPS
Q_s = Sampling flowrate = 2.83 LPM
t_d = Dead time = 4 µs



The concentration at 10% coincidence loss is 1,137 cm^{-3}.

Conclusion

1. OPC can be applied to measure high concentration aerosols as long as the concentration of minimum size bin of OPC does not exceed the 10% coincidence loss concentration even when there are many particles smaller than the detection limit of OPC.
2. Coincidence loss curve follows Poisson distribution rather than Erlang distribution.
3. Responses of 2 OPCs for high concentration aerosols are consistent if the calibration is properly conducted according to ISO 21501-4, which implies that we may introduce a correction scheme to retrieve true concentration from measured concentration.

Thank you for your kind attention