Particle Measurement & Technology Laboratory

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Mapping the Performance of a Versatile Water-based Condensation Particle Counter (vWCPC) with Numerical Simulation and Experimental Study

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- Accurate airborne aerosol measurements are needed **in different altitudes** and diverse climate regimes.
- Identify a potential CPC that **avoids the health and safety concerns** of butanol-based CPCs.
- Characterize the versatile water CPC **at reduced pressures** for atmospheric airborne research.

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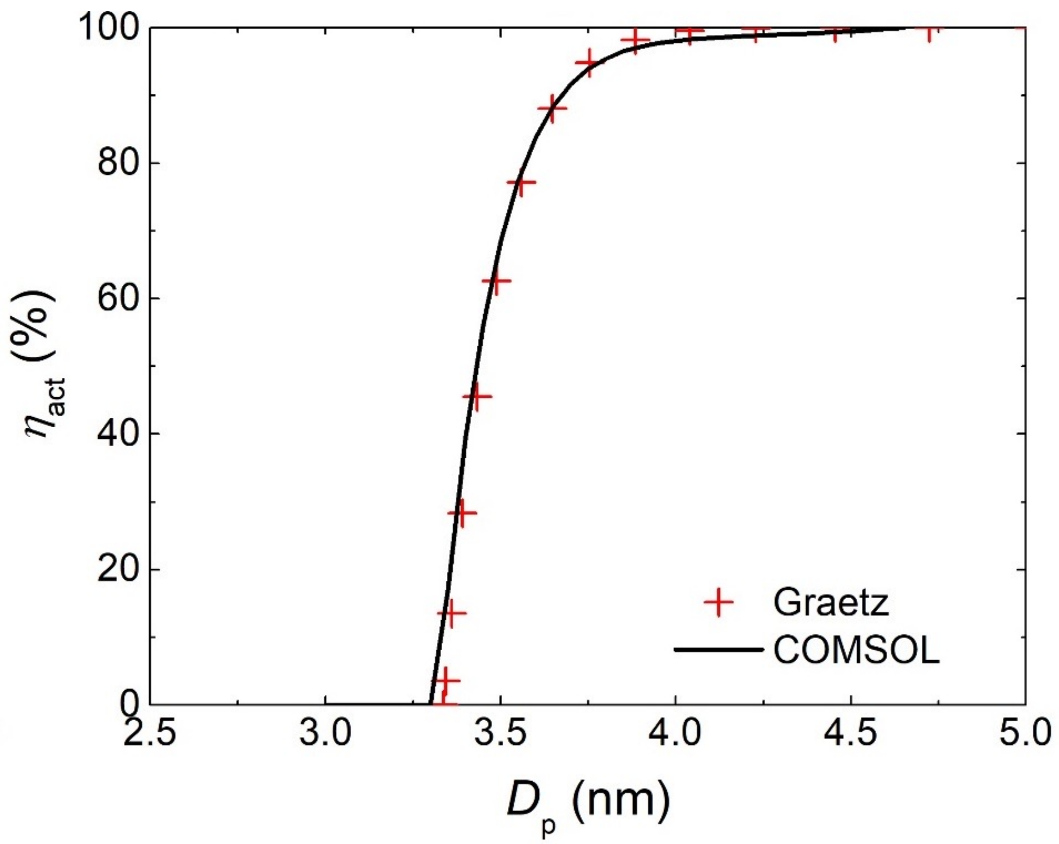
https://tsi.com/products/particle-counters-and-detectors/condensation-particle-counters/versatile-water-based-condensation-particle-counter-3789/.

- **Numerical modeling** is advantageous in studying the vWCPC performance with various operating parameters.
- Our previous study shows that **COMSOL** and analytical **Graetz solution** show excellent agreement.

Activation efficiency



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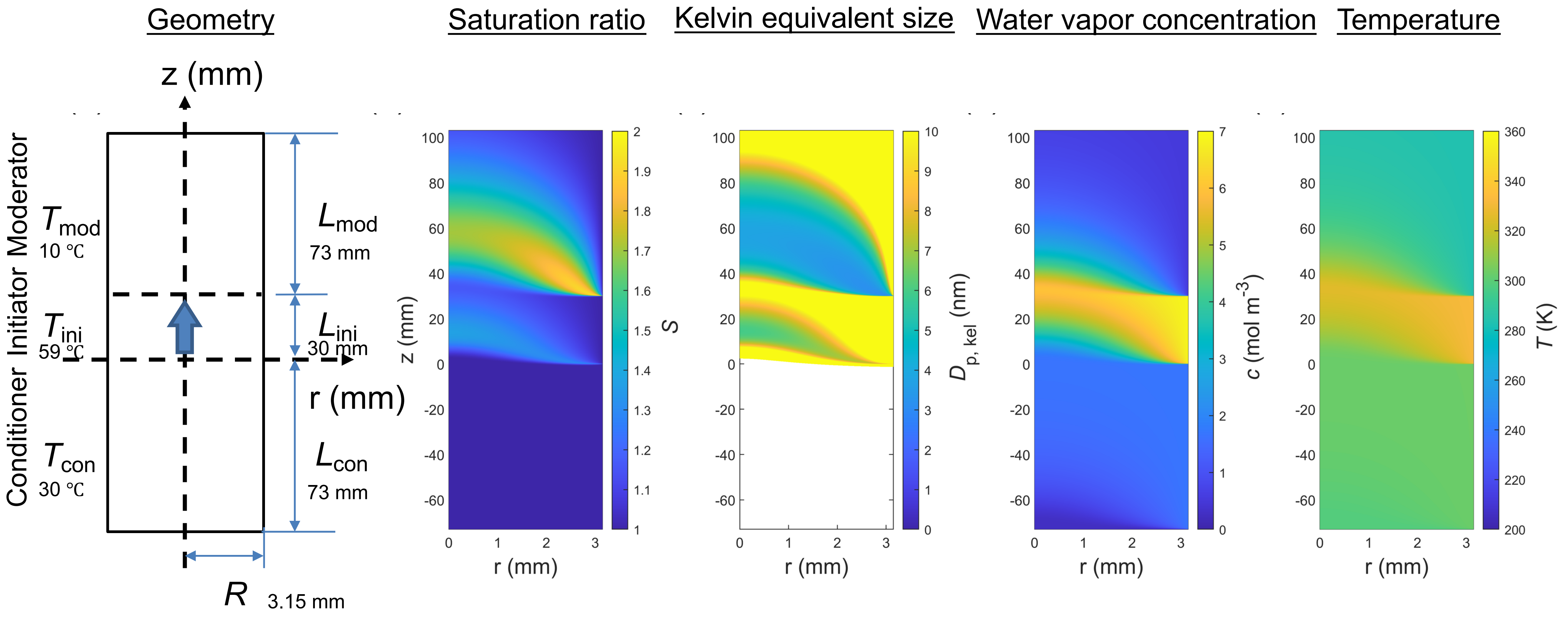
Hao, et al. (2021). Optimizing the activation efficiency of sub-3 nm particles in a laminar flow condensation particle counter: Model simulation. J. Aerosol Sci.

- Determine **particle activation** and **droplet growth** in simulation:
    - saturation ratio profile
    - activation efficiency
    - particle growth

- Investigate the effects of **operational factors** on particle activation and droplet growth:
    - operating temperature
    - inlet pressures (30 - 101 kPa)
    - geometry

- Compare the detection efficiency of **laboratory experiments** and modeling work.

Simulation geometry and spatial distribution



Simulation plan

The default settings of vWCPC:

- T_{con}, T_{ini}, and T_{mod} of 30, 59, and 10 ℃.
- The aerosol flow rate is 0.3 L min^{-1}.
- The relative humidity (RH) of inlet flow is set at 20%.
- The water vapor is saturated at the wall.
- The inlet pressure (P) is 101 kPa (1 atm).

T_{con}: Conditioner temperature
T_{ini}: Initiator temperature
T_{mod}: Moderator temperature
T_{mid}: Temperature midpoint
D: Tube diameter
L_{ini}: Initiator length

Task	T_{con} (°C) – T_{ini} (°C)	T_{mod} (°C)	T_{mid} (°C)	P (kPa)	D (mm)	L_{ini} (mm)
1	(25, 30, 35) – (55, 60, 65)	10	–	101	6.3	30
2	24–56, 27–59, 30–62	10	40, 43, 46	30–101	6.3	30
3	27–59, 30–59	10	–	30–101	6.3	30
4	30–59	10	–	51, 101	4, 5, 6.3, 8	30
5	30–59	10	–	51, 101	6.3	10, 20, 30, 40, 50

Theory of particle activation

$$S = \frac{p}{p_s}$$

$$D_{p,kel} = \frac{4\sigma v_m}{kT\ln(S)}$$

$$\eta_{act} = \frac{\int_0^{R_{act}} 2\pi r w N \mathrm{d}r}{Q_v N_0}$$

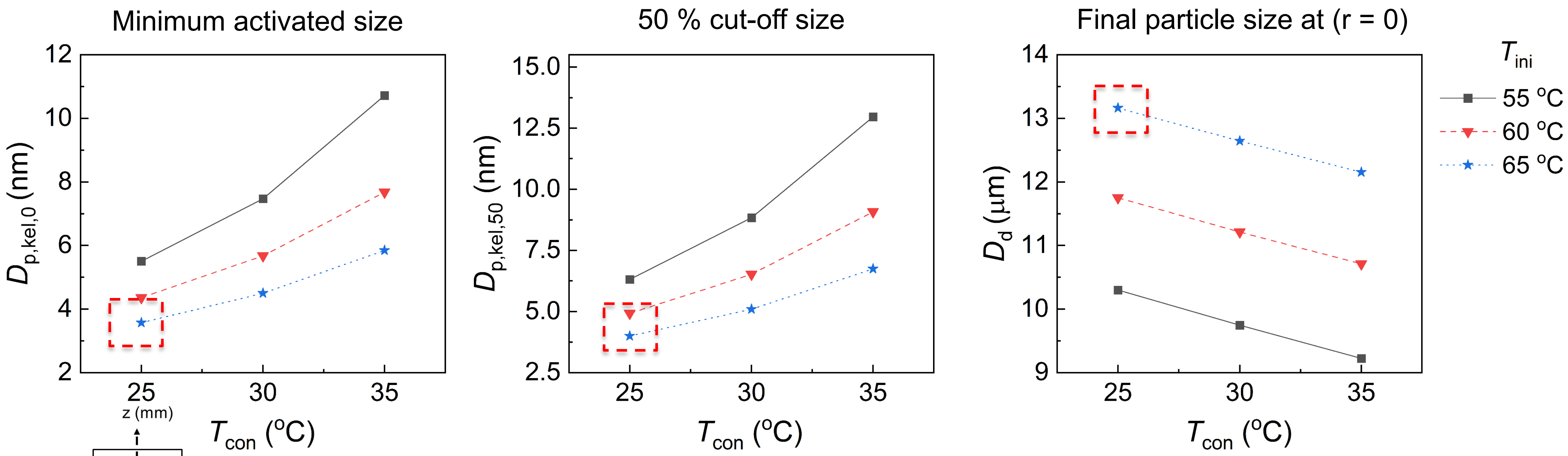
Theory of droplet growth

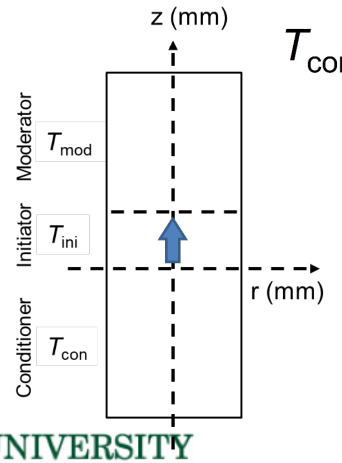
$$\frac{\mathrm{d}D_p}{\mathrm{d}t} = \frac{4D_v{}'M}{\rho}\frac{(C - C_d)}{D_p}$$

$$\frac{\mathrm{d}T_d}{\mathrm{d}t} = \frac{3}{c_p \rho D_p}\left(H_{vap}\rho\frac{\mathrm{d}D_p}{\mathrm{d}t} - 4k_g{}'\frac{(T_d - T)}{D_p}\right)$$

- $D_{p,kel,0}$: smallest size of particle that can be activated
- $D_{p,kel,50}$: size of particle that has a 50% activation efficiency
- D_d: final growth droplet size

Simulation results: Comparisons of temperature-dependent particle activation and droplet growth





- The activated size becomes **smaller** as the ΔT increases.
- Final particle size D_d is the **greatest** with size of 13.20 µm at the temperature of **25–65–10 ℃**.

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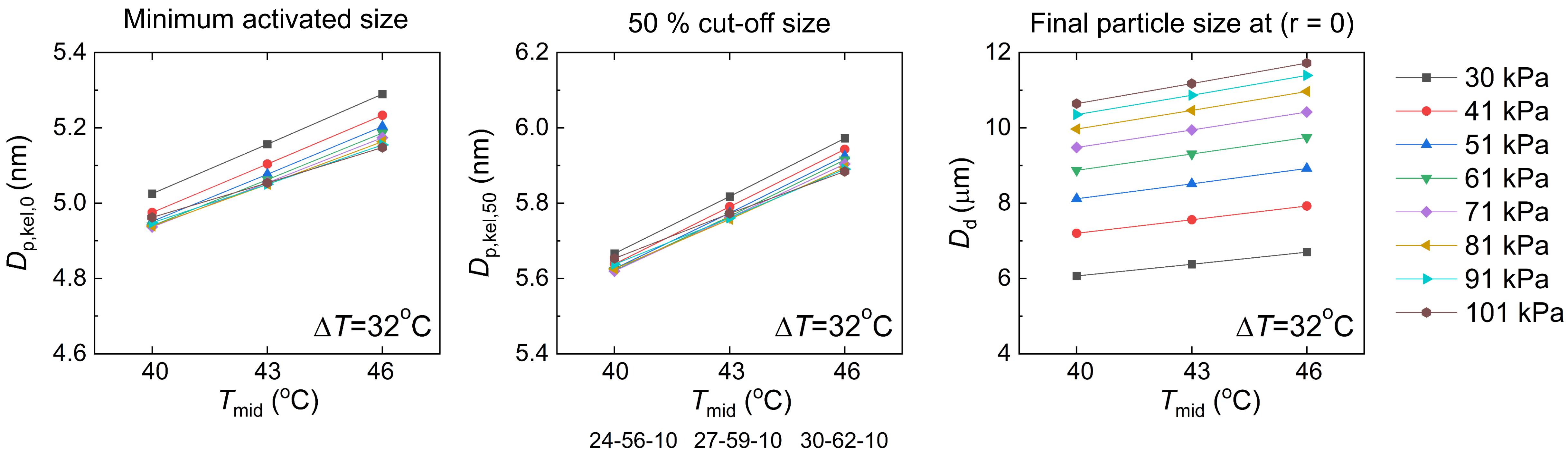

- **Improved** particle activation can be achieved by **lowering** the temperature midpoint.
- By lowering the temperature midpoint by 6 ℃, D_d becomes smaller **by 14%**, and D_d decreases **by 45%** with reduced pressure.

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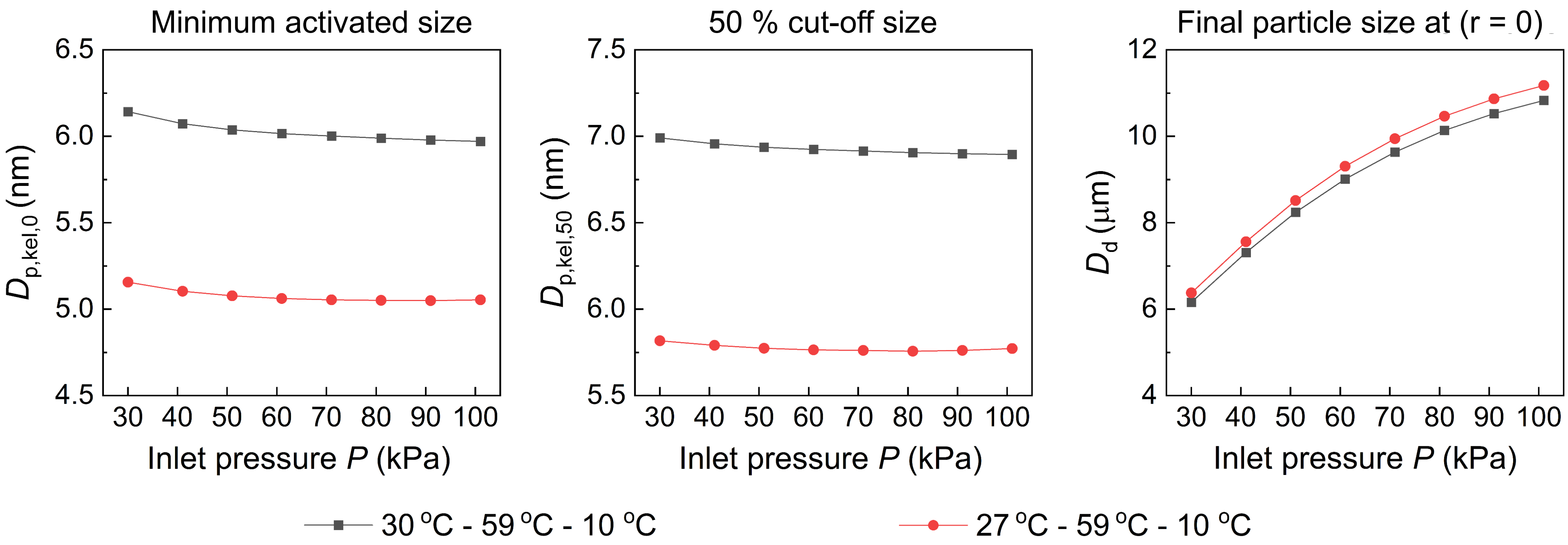
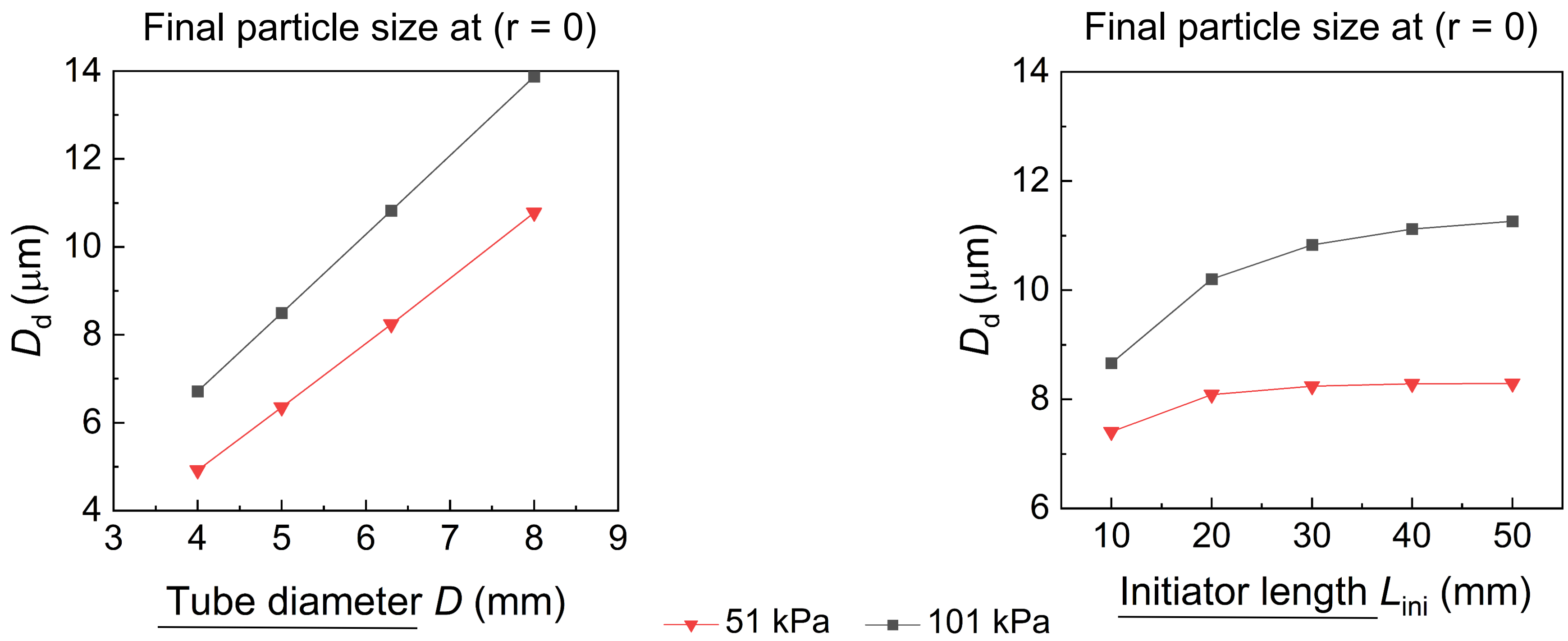
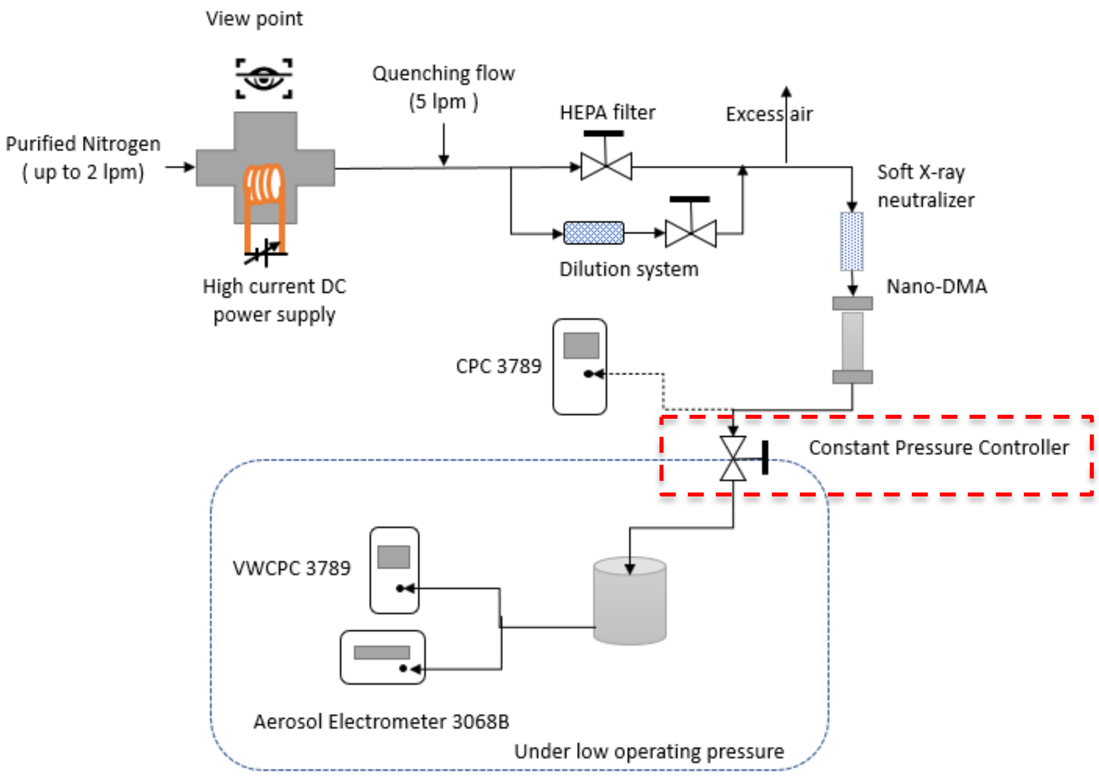


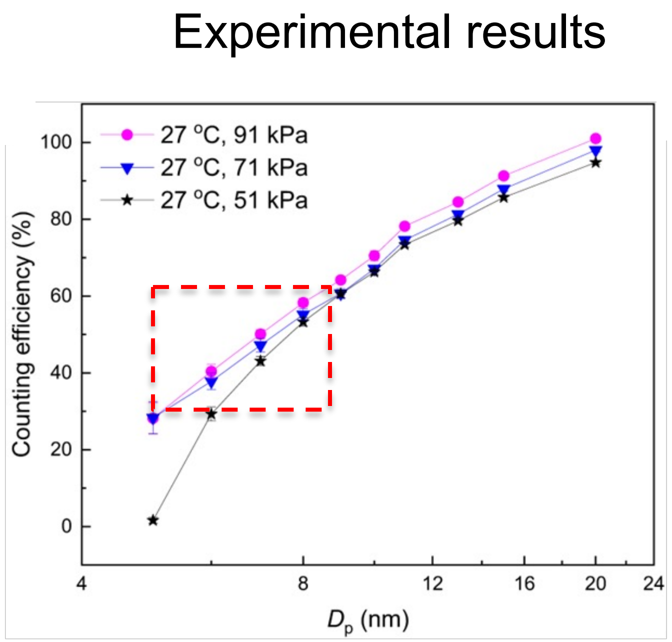
- **2 - 3% greater** $D_{p,kel,0}$ and $D_{p,kel,50}$ under reduced inlet pressures.
- A smaller final droplet size (~ **40 % reduction**) was observed at reduced pressure of 30 kPa.
- Lower inlet pressure, the final droplet size **reduced more** notably.

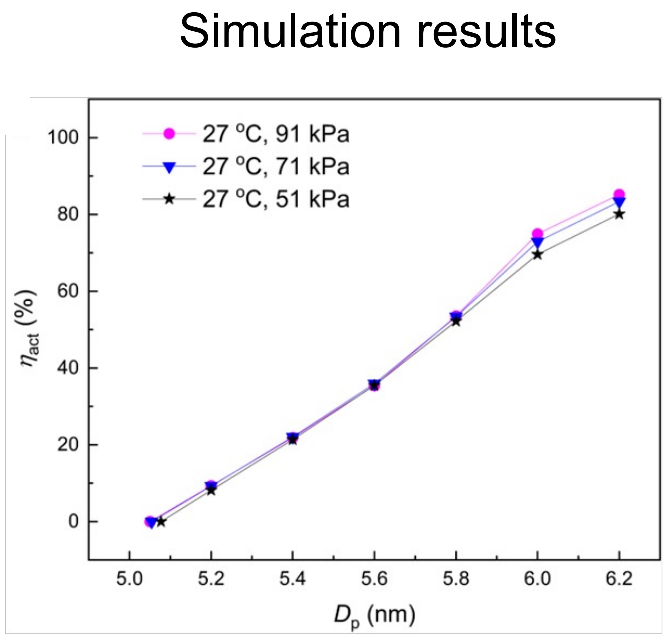


- **No noticeable changes** in particle activation.
- An **increased tube diameter *D*** and **initiator length L_{ini}** improve the performance of particle growth.

Experimental measurement of detection efficiency agrees well with simulation results







- The counting efficiency slightly **decreases** with the decrease in the operating pressure.
- The cut-off size in both experimental and simulation results is in the range of **5 - 7 nm**.

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Mei, et al. (2021). Simulation-aided characterization of a versatile water-based condensation particle counter for atmospheric airborne research. Atmospheric Measurement Techniques.

Summary

- This study guides further optimization of the performance of vWCPCs for accurate detection of particles and **atmospheric aerosol measurement applications**.

- Temperature effects
  - **Increased** temperature difference ΔT improved vWCPC particle activation and droplet growth.
  - **Decreased** temperature midpoint T_{mid} improved vWCPC particle activation, but not for growth.

- Pressure effects
  - **40 % reduction** in final droplet size was obtained at a reduced pressure of **30 kPa** compared to standard pressure (101 kPa).

- Geometry effects
  - **Increased** tube diameter improved the particle growth.
  - **Increased** initiator length **limited impacts** on improving vWCPC performance.

- Experimental measurement of detection efficiency **agrees** well with simulation results.

Thank you!

Q&A

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Hao, et al. (2023) Mapping the performance of a versatile water-based condensation particle counter (vWCPC) with numerical simulation and experimental study. Atmospheric Measurement Techniques.

allowed particle growth time

$$t_g \sim D^2 L^* / Q_v,$$

homogeneous nucleation rate (I)

$$I = 2 \times \left[\frac{p}{(2\pi mkT)^{1/2}} \right] \times \left(n v_m^{2/3} \right) \times \left[\frac{\sigma v_m^{2/3}}{kT} \right]^{1/2} \times \exp\left[- \frac{16\pi\sigma^3 v_m^2}{3(kT)^3 (\ln S)^2} \right]$$