An Ultrafine Particle Number Measurement System Operating Under Wide Temperature Range

Wide Temperature Condensation Particle Counter(WTCPC)

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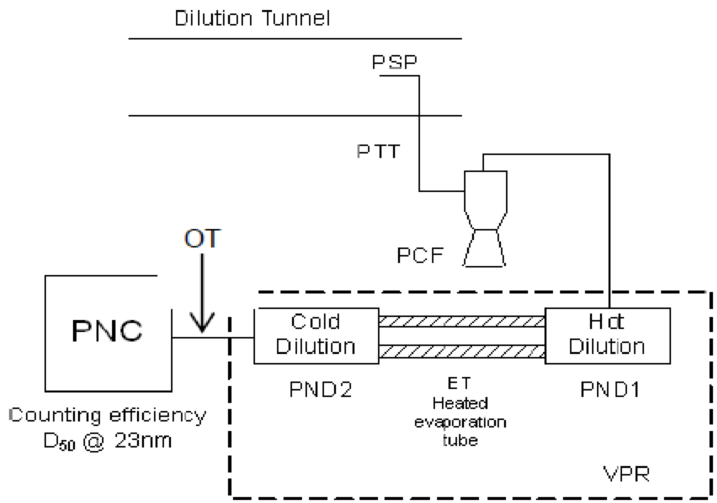
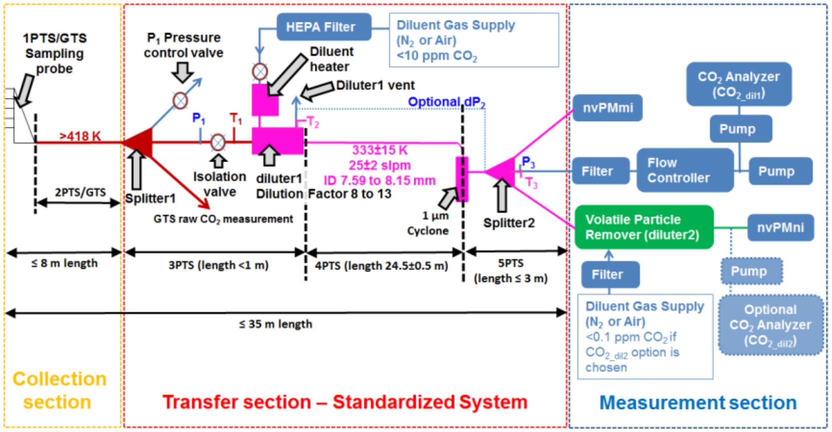
Background: Nanometer Particle Number (PN) Regulations

PN regulation for vehicles

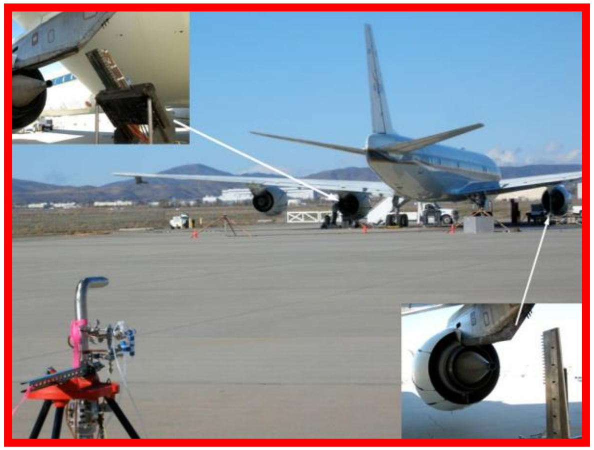


A recommended particle measurement system (PMP)

PN regulation for aviation



A recommended nvPM measurement system (SAE E31)



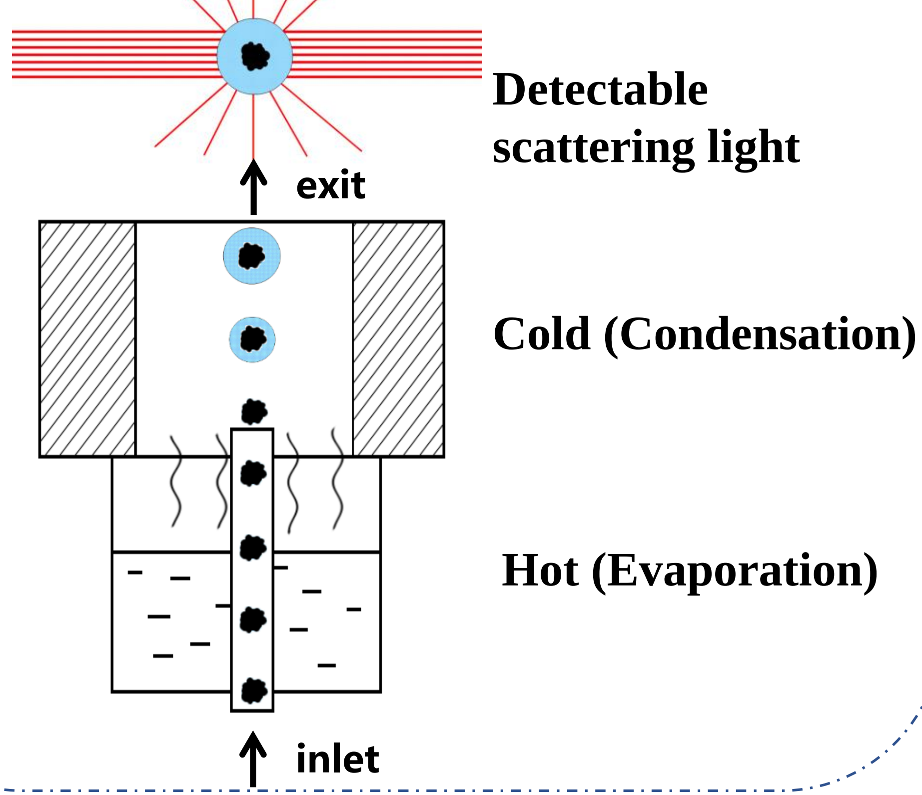
More industries (e.g. filtration material) will introduce PN regulations.

Condensation Particle Counter (CPC) is the only compliant method*

Traditional techniques: filter-based, thermoacoustic, etc.

Nanometer particles are too small

Particles grow via condensation and count (CPC)

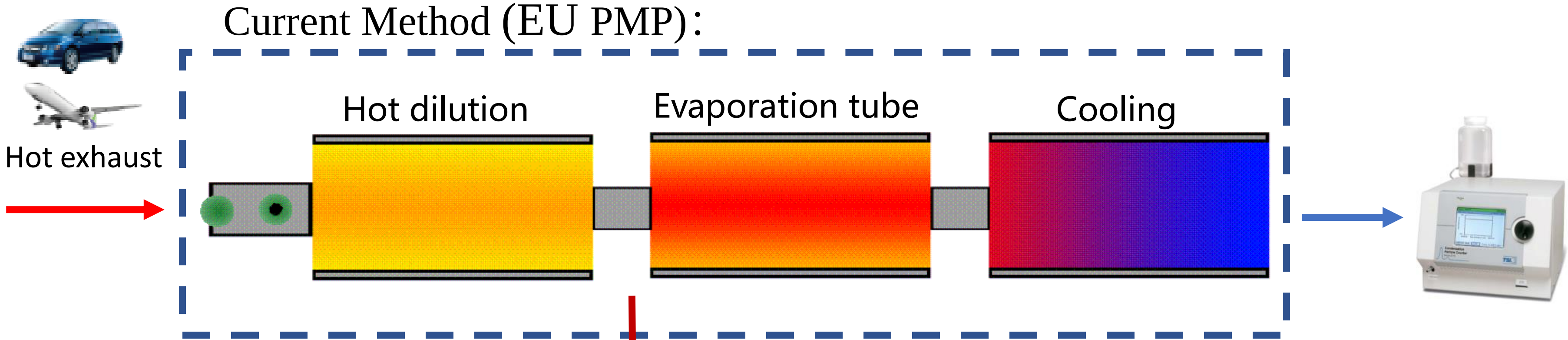


*ICAO SAE E31 Annex. 16 and EU PMP ECE No 83.

Background: Traditional Method ‘Uncertain’

Hot exhaust PN measurement: first cooling and then count PN using CPC. The measurement error is up to 40% (J.AerosolSci.,2011,42:883–897).

Current Method (EU PMP):



Cooling results in: 1. Uncertainty of coupling relationship between self-condensation of VOC and heterogeneous condensation of particles; 2. Complex stress of nanoparticles under large temperature gradient.

Count PN at high temperature?

Use room-temperature CPCs? ✖

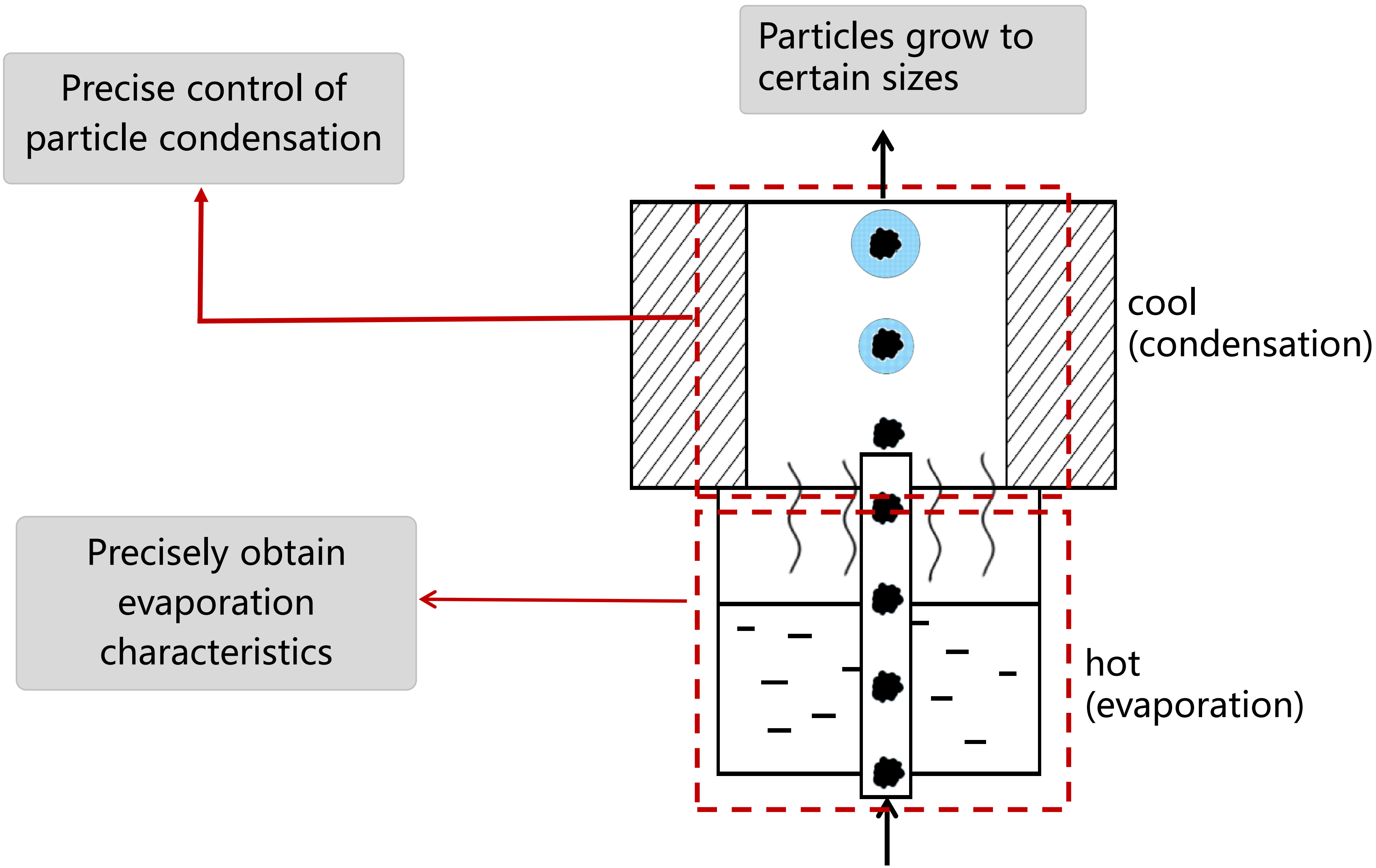
It is difficult to count PN after condensation at high temperature.

Design new working liquid to realize wide temperature CPC

	Condensation working liquid	Working temperature
Amercian TSI 9001 CPC	water	<35℃
German Grimm 5400 CPC	N-butyl alcohol	<40℃
Amercian TSI 9310 CPC	Isopropyl alcohol	<40℃
Finland Airmodus A10 CPC	Diethylene glycol monoethyl ether	<45℃
Beihang WTCPC	Non-ideal liquid mixture	10--200℃

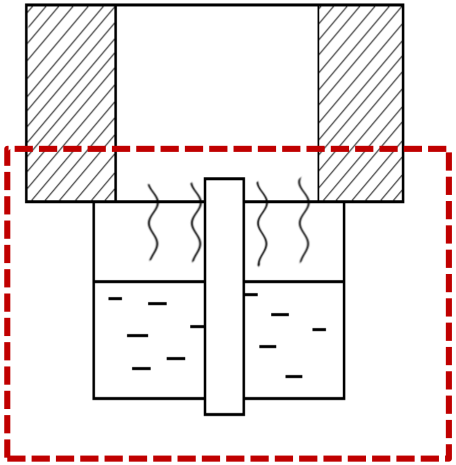
All existing CPCs use pure substances while WTCPC adopts a strongly non-ideal mixture as condensation working liquid.

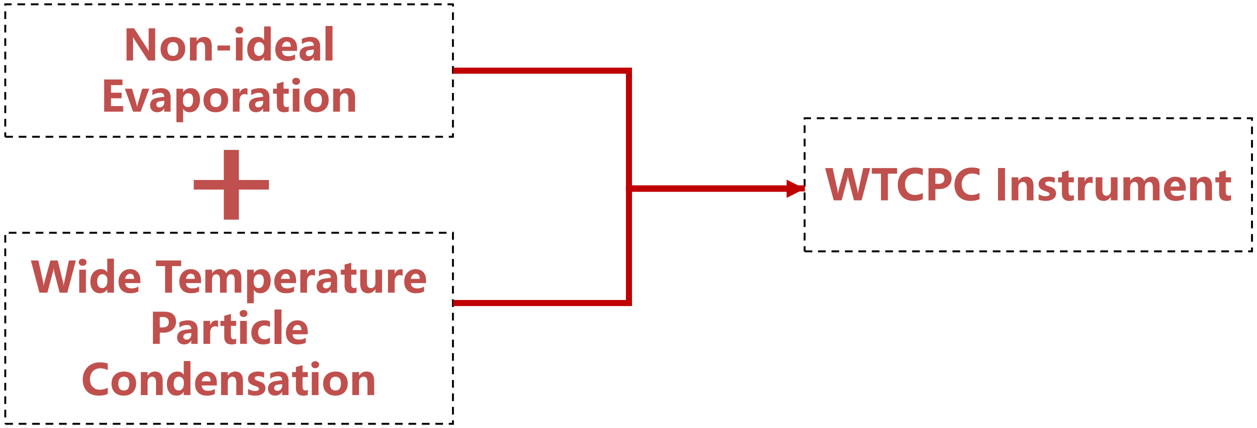
Design new working liquid to realize wide temperature CPC



Challenge for predicting evaporation and condensation due to non-ideality.

Innovation 1: Revealing the evaporation mechanism of non-ideal working liquid





Resolve two inaccuracies (inaccurate evaporation heat and inaccurate vapor components)

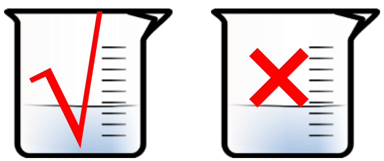
Innovation 1: Revealing the evaporation mechanism of non-ideal working liquid

Prob. Low calculation accuracy of latent heat of evaporation

$$\dot{m} = 2\pi d\rho D ln\left(1 + \frac{C_{PV}(T_\infty - T_0)}{L_{eff}}\right)$$

Evaporative latent heat

Simple substance



Non-ideal solution

Equation Clausius-Clapeyron

Inherent defect:

C-C equation ignores the chemical potential increase caused by mixture non-ideality.

C-C assume: $$dG = \sum_{i=1}^{n} d(x_i\mu_i)$$

Non-ideal solution: $$dG \neq \sum_{i=1}^{n} d(x_i\mu_i)$$

Difficuty The chemical potential increase is difficult to calculate due to the lack of high temperature data

$$dG = \sum_{i=1}^{n} d(x_i\mu_i) + f(x_i, \theta_m, \Psi_{m,n}) \ ?$$

$$f(x_i, \theta_m, \Psi_{m,n}) = \sum x_i \sum_{k} N_{ki}\left(Q_K RT^2\left(\frac{\sum_m \theta\Psi'_{mk}}{\sum_m \theta\Psi_{mk}} - \sum_{m}\frac{\theta_m\Psi'_k m}{\sum_n \theta_n\Psi_{nm}} - \frac{\theta_m\varphi_{km}(\sum_n \theta_n\Psi'_{mn})}{(\sum_n \theta_n\Psi_{mn})^2}\right) - H^*_{ki}\right)$$

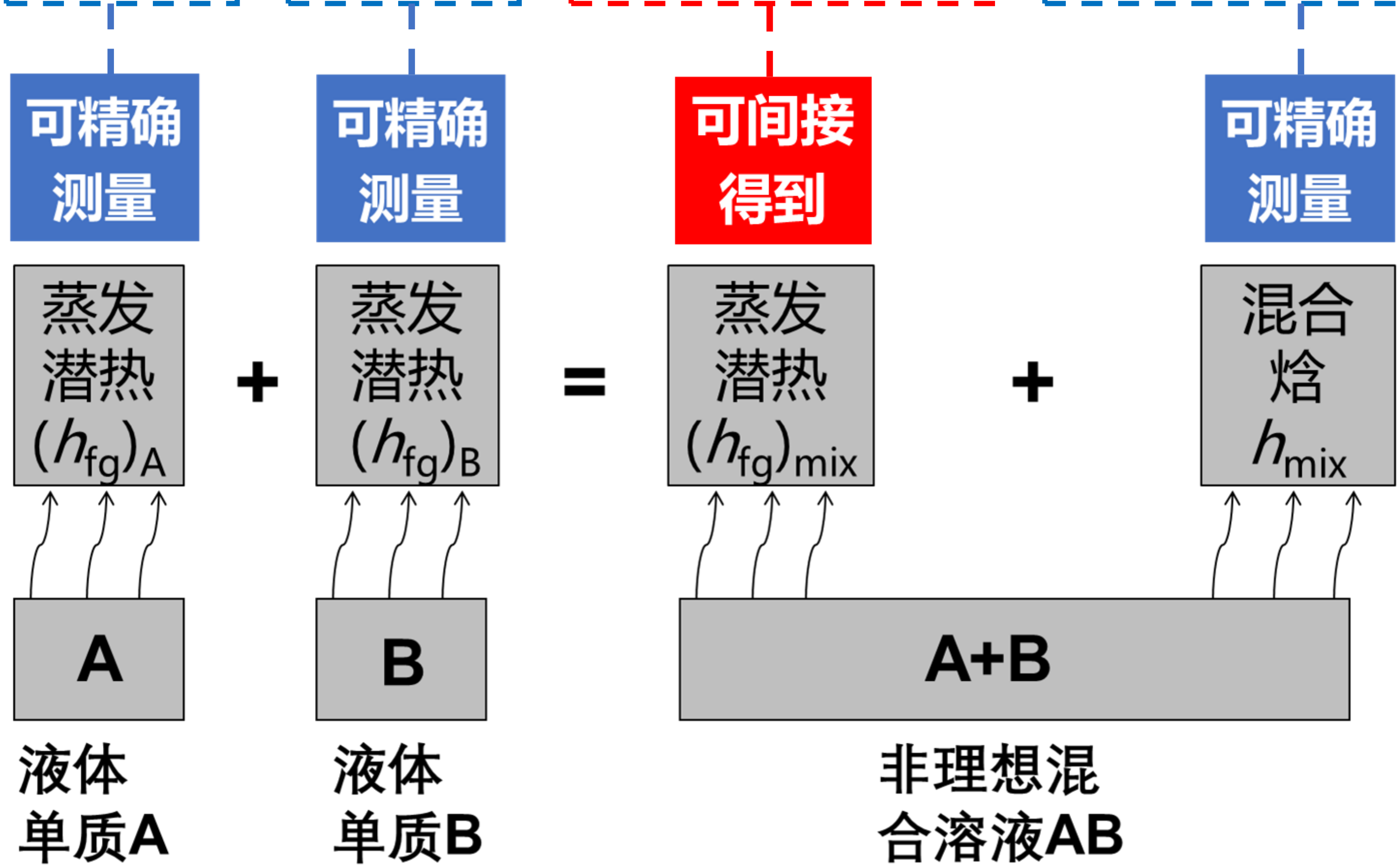
Solution Obtain the latent heat of evaporation indirectly. No need of direct calculation via C-C equation.

Innovation 1: Revealing the evaporation mechanism of non-ideal working liquid

New method

Thermodynamic derivation → Indirect measurement of latent heat

$$m_A(h_{fg})_A + m_B(h_{fg})_B = (m_A + m_B)(h_{fg})_{AB} + \Delta T[m_A(c_p)_A + m_B(c_p)_B]$$



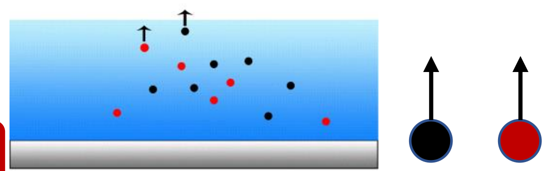
Chen* et al., Energ. Fuel., 2011, 25; Chen* et al., Fuel., 2012, 96.

Innovation 1: Revealing the evaporation mechanism of non-ideal working liquid

Reveal the reason for the inaccuracy of vapor component prediction for non-ideal mixtures.

Problem

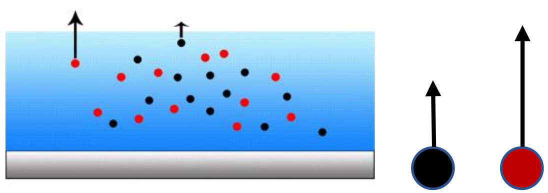
Traditional model (Raoult and Henry law)



$$\begin{cases} p_A = p_A^0 x_A \\ p_B = p_B^0 x_B \end{cases}$$

Components evaporate without interference

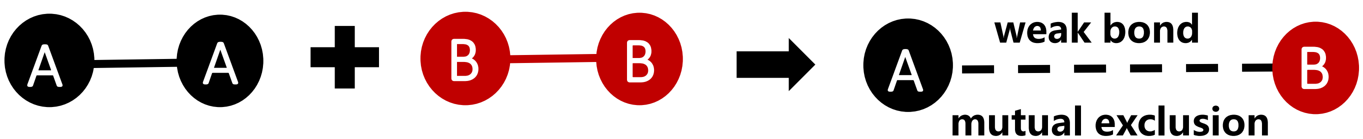
Non-ideal liquid (laws invalid)



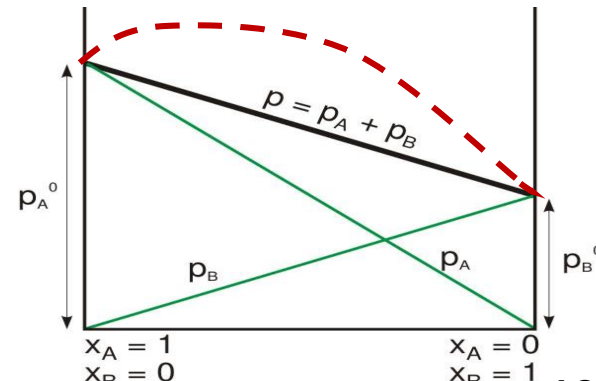
$$\begin{cases} p_A \neq p_A^0 x_A \\ p_B \neq p_B^0 x_B \end{cases}$$

Incompatible components and accelerated evaporation rate

physical mechanism



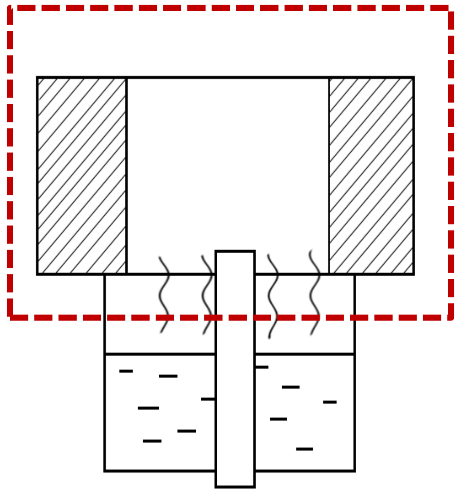
Thought



Quantitatively characterize the component evaporation interference, consider the relationship between component diffusion rate and evaporation rate, establish the unsteady evaporation mechanism (WM,FZ,DC)

Chen* et al., Int. J. Heat Mass Trans,2016.

Innovation 2：Revealing the mechanism of particle condensation growth



Non-ideal evaporation

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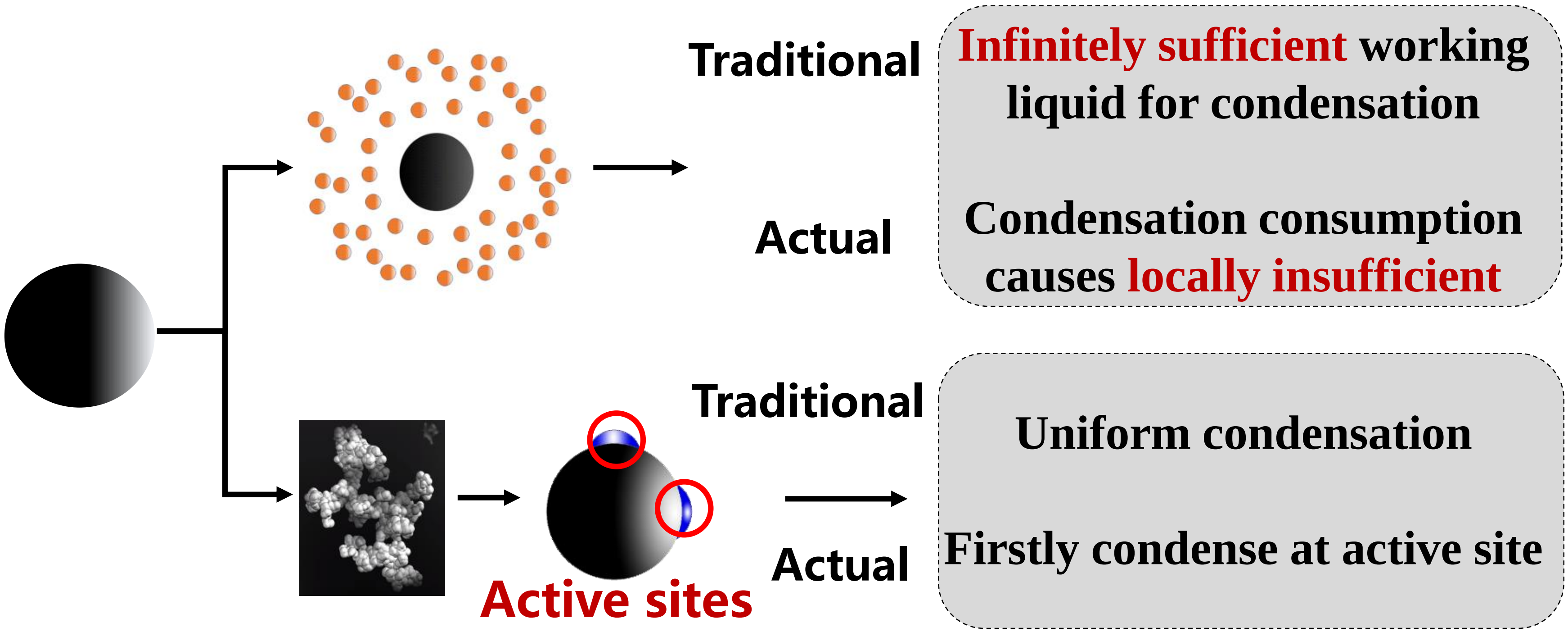
Wide temperature particle condensation

→ WTCPC

Tackle the uncertainty of predicting particle condensation growth rate.

Innovation 2：Revealing the mechanism of particle condensation growth

Question **Prediction of particle condensation rate is inaccurate**



Idea

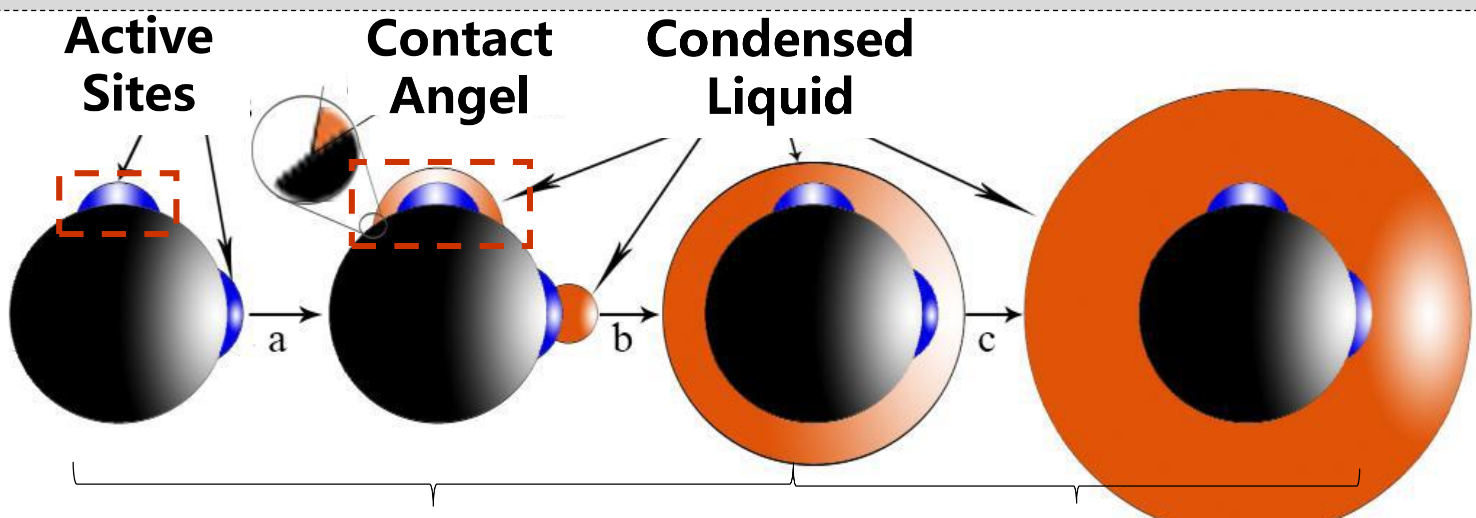
Proposing a multi-stage condensation model incorporating the effects of vapor insufficiency and active sites.

Innovation 2：Revealing the mechanism of particle condensation growth

New Model A multi-stage condensation model involving **active sites**

Active site numbers: $n = f(\rho, A_p) = \rho n_{p0} z A_{P0} = \rho k_f (\frac{d_g}{d_{p0}})^{D_f} z \pi {d_{p0}}^2$

$\rho \sim N(\mu, \sigma^2)$: active site density.



Heterogeneous condensation growth rate

$$J = f(\mathrm{n}, J_{hom})$$

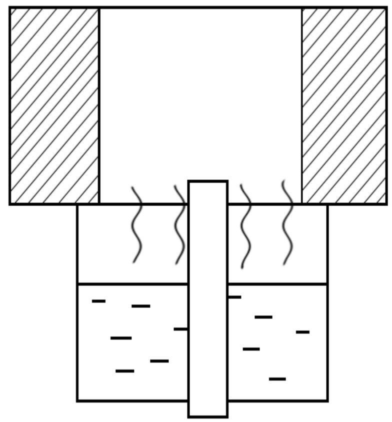
$$= Ke^{\frac{-\Delta G_{\mathrm{hom}} f(\theta, n)}{kT}}$$

Homogeneous condensation growth rate

$$J = e^{(A+BT)} Ke^{\frac{-\Delta G_{hom}}{kT}} \quad (d < d_c)$$

$$J = \frac{2\pi D_{vg} v_m d_p}{k} \left(\frac{P_\infty}{T_\infty} - \frac{P_d}{T_d}\right) f(Kn_v) \; (d > d_c)$$

Innovation 3: Develop wide temperature condensation particle counter(WTCPC)



non-ideal evaporation

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wide temperature particle condensation

→ WTCPC prototype

Innovation 3: develop wide temperature CPC (WTCPC)

Innovation 3： Develop wide temperature condensation particle counter(WTCPC)

Challenge

The grown particles are still at high temperature (200℃), and normal photoelectric sensors cannot count them.

Difficulty

1. High temperature causes low SNR of sensors

2. Optical devices would be smeared if we cool down the carrier gas.

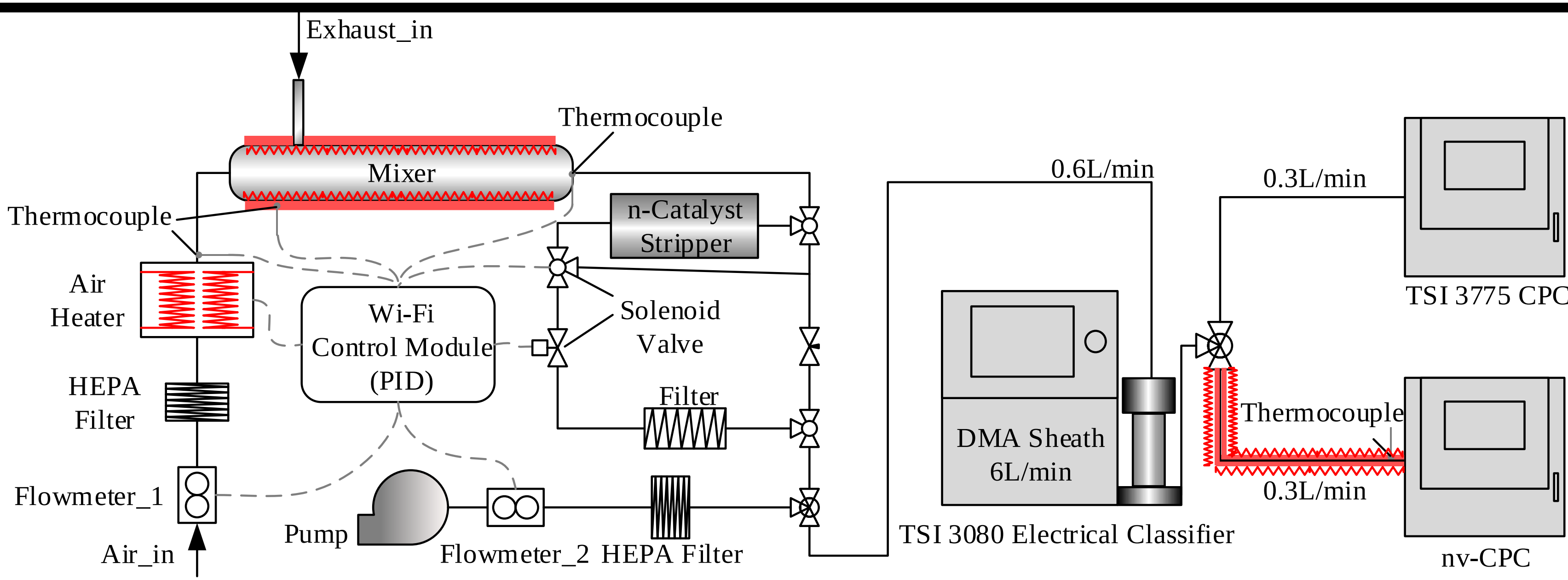
Idea

Light path simulation

Optimized thermo and Pneumatic structure

→ OPC Prototype → Inversion algorithm → PSD data

Calibration of WTCPC counting efficiency (generating, dilution, counting)




FINAL DRAFT

INTERNATIONAL STANDARD

ISO/FDIS 27891

ISO/TC 24/SC 4
Secretariat: DIN
Voting begins on: 2014-07-02
Voting terminates on: 2014-09-02

Aerosol particle number concentration — Calibration of condensation particle counters

Densité de particules d'aérosol — Étalonnage de compteurs de particules d'aérosol à condensation

Reference number ISO/FDIS 27891:2014(E)

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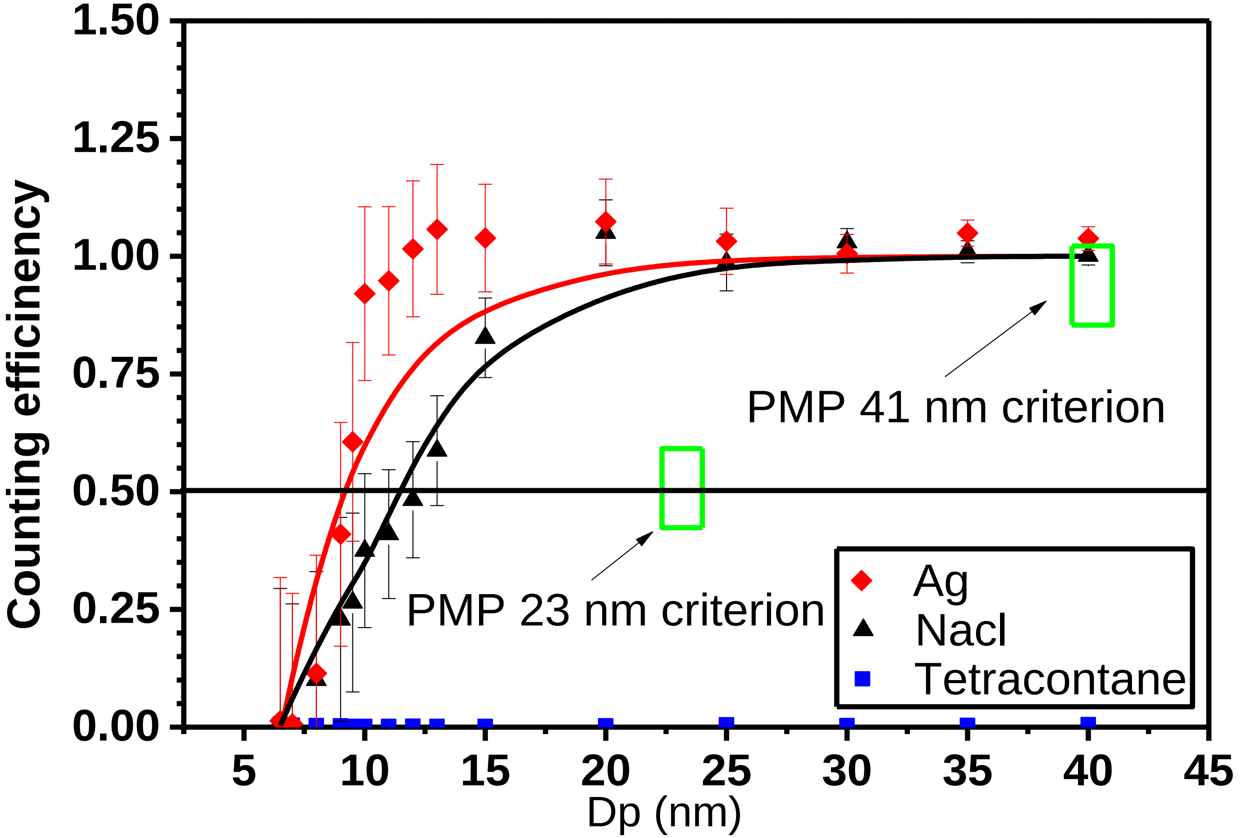
Calibration data for counting efficiency of WTCPC

Calibration against TSI 3775 CPC as reference



$d_{90,\ NaCl}$ = 20 nm
$d_{90,\ Ag}$ = 16 nm

$d_{50,NaCl}$ = 12 nm
$d_{50,Ag}$ = 10 nm

A new version WTCPC is being developed to meet PN10 requirement.

Summary

	Existing CPC (TSI, Grimm etc.)	WTCPC (BUAA)
Temperature	0-50℃	10-200℃
Particle size	1-1000 nm	10-1000 nm (size bins)
Pre-conditioning	Need cooling	No need of cooling

Aiming at counting PN at high temperature, a new working liquid was designed and associated non-ideality effects were investigated to develop a WTCPC with higher measurement reproducibility.