Cornell University

Quantifying the Effects of the ***Mixing Process*** in Fabricated ***Dilution Systems*** on ***PM*** Emission Measurements

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Acknowledgment

- PhD students: Y. Jason Wang, Bo Yang, Zheming Tong
- Data Sharing
  - CMU: Allen Robinson and Eric Lipsky
  - Tampere U. of Tech, Finland: Jorma Keskinen and Topi Ronkko
  - Dekati: Engineering drawing for ejector dilutor
- Alan Leinbach at USEPA for critiquing the final report

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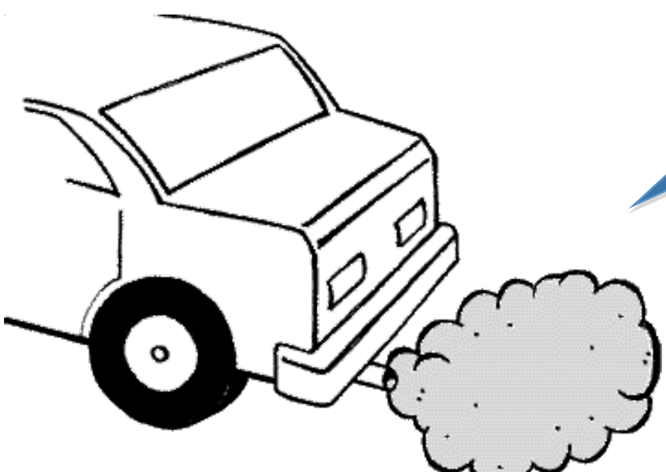
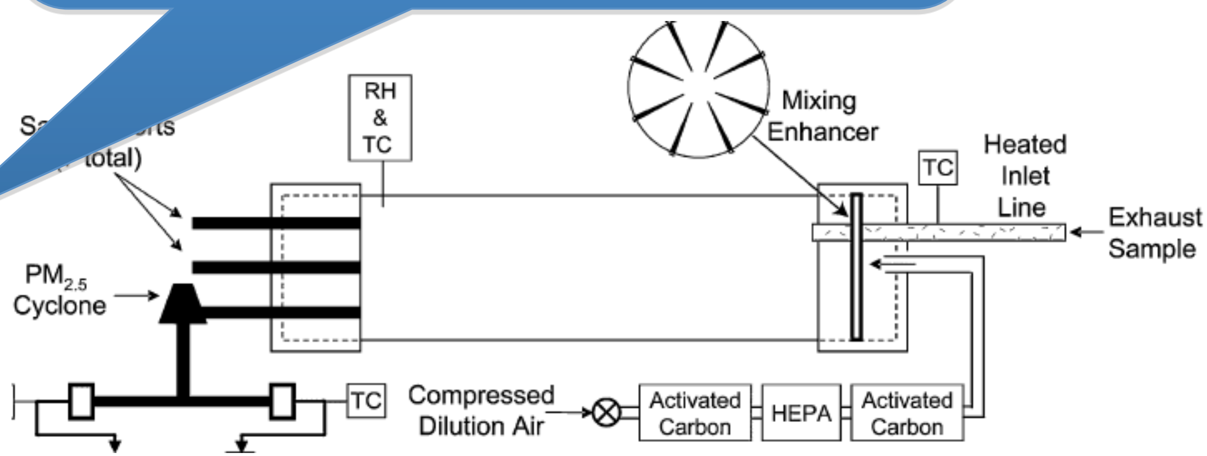
A Tale of Two "Reactors"

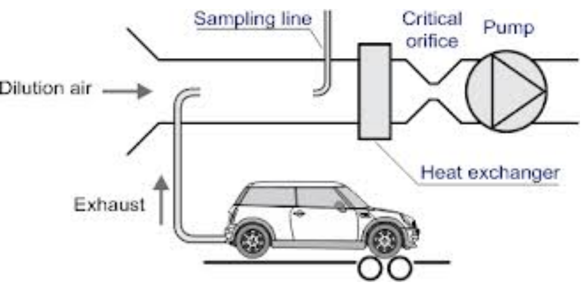
- Atmosphere and laboratory dilution tunnels can be regarded as "***turbulent reactors***":
  - cooling the exhaust
  - generating new p
  - changing the prop
- Same nature!

3-D turbulent reacting flows, coupling of transport and transformation





Aerodynamic vs. Mixture Properties



Group I. Aerodynamics	Fixed parameter: Tunnel configuration	Mixing type of the dilution tunnel: T-mixing dilution tunnel,[2,4] coaxial mixing dilution tunnel,[2] perforated tube diluter (Dekati Ltd.), ejector diluter (Dekati Ltd.), rotating disk diluter (Matter Engineering Inc.), etc.
		The mixing enhancer: fan shape plate,[2] orifice plate, baffle, etc.
	Variable parameter: Operating condition	Dilution ratio (*DR*) at the end of the dilution tunnel
		Residence time inside the dilution tunnel
Group II: Mixture properties	Properties of engine exhaust: temperature, water content, sulfuric acid concentration, *OC* concentration and composition, size distribution of the primary soot-mode particles, etc.	
	Properties of dilution gas: temperature of dilution gas, relative humidity (*RH*), particle size distribution, *OC* concentration and composition, type of dilution gas (e.g., pure nitrogen or air), etc.	

Wang et al. (2013) ES&T, 47:889-898

Level of Scientific Understanding

Qualitative: **Poor** *Quantitative*: **Very Poor**	Group I. Aerodynamics	Fixed parameter: Tunnel configuration	Mixing type of the dilution tunnel: T-mixing dilution tunnel,[2, 4] coaxial mixing dilution tunnel,[2] perforated tube diluter (Dekati Ltd.), ejector diluter (Dekati Ltd.), rotating disk diluter (Matter Engineering Inc.), etc.
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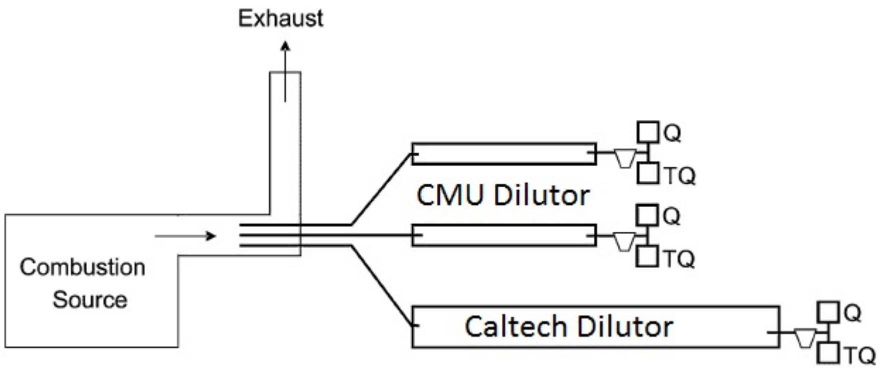
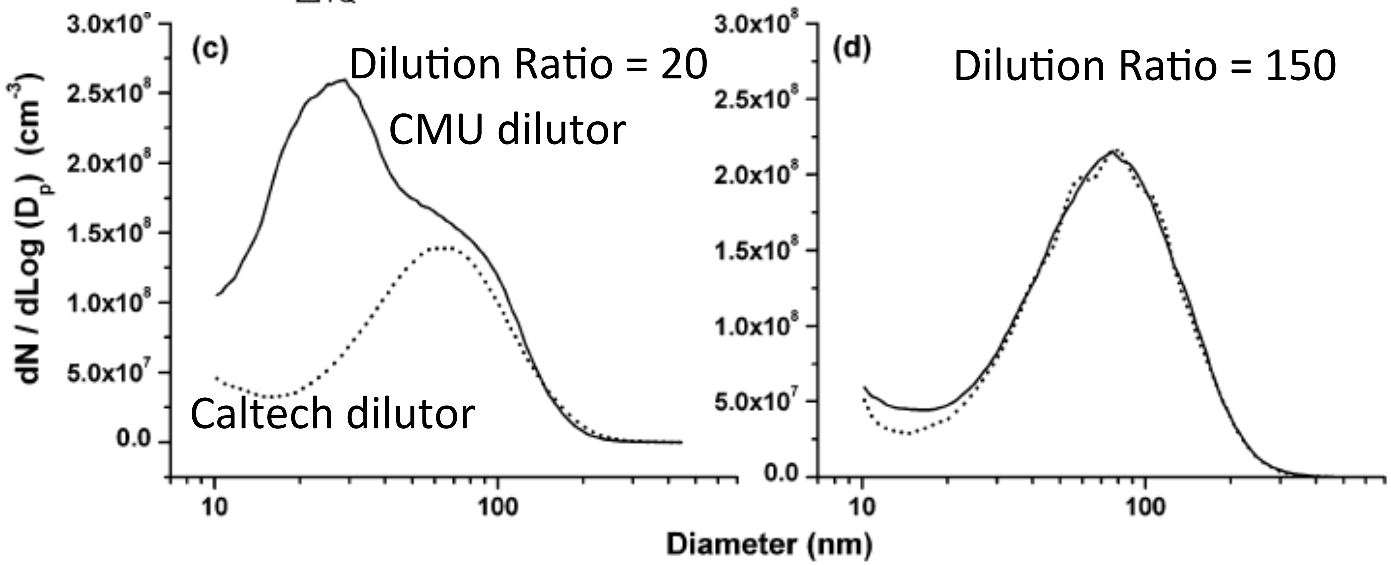




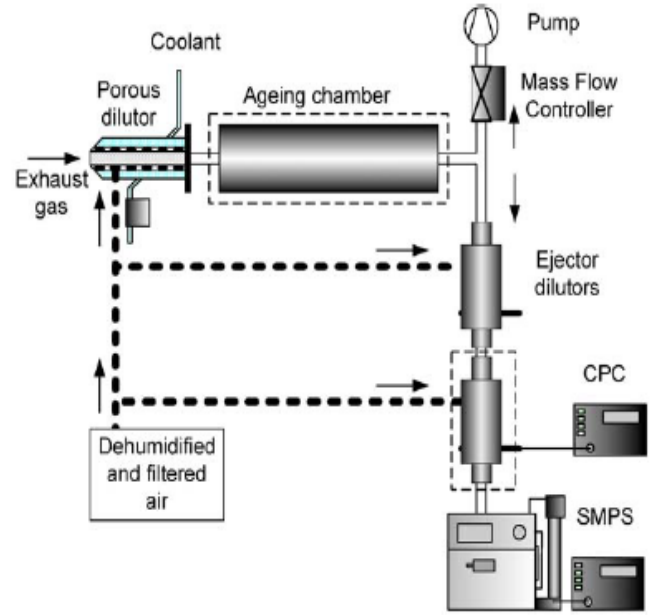
Dilution-corrected number size distributions measured during two diesel intercomparison experiments between the CMU dilutor (the dash line) and the Caltech dilutor (the solid line) (Lipsky and Robinson, 2005)

The measurement results from different dilution tunnels are not directly comparable as they are sensitive to dilution conditions.

On-Road Chasing

- Capture the real world vehicle emissions
- Results depending on atmospheric conditions

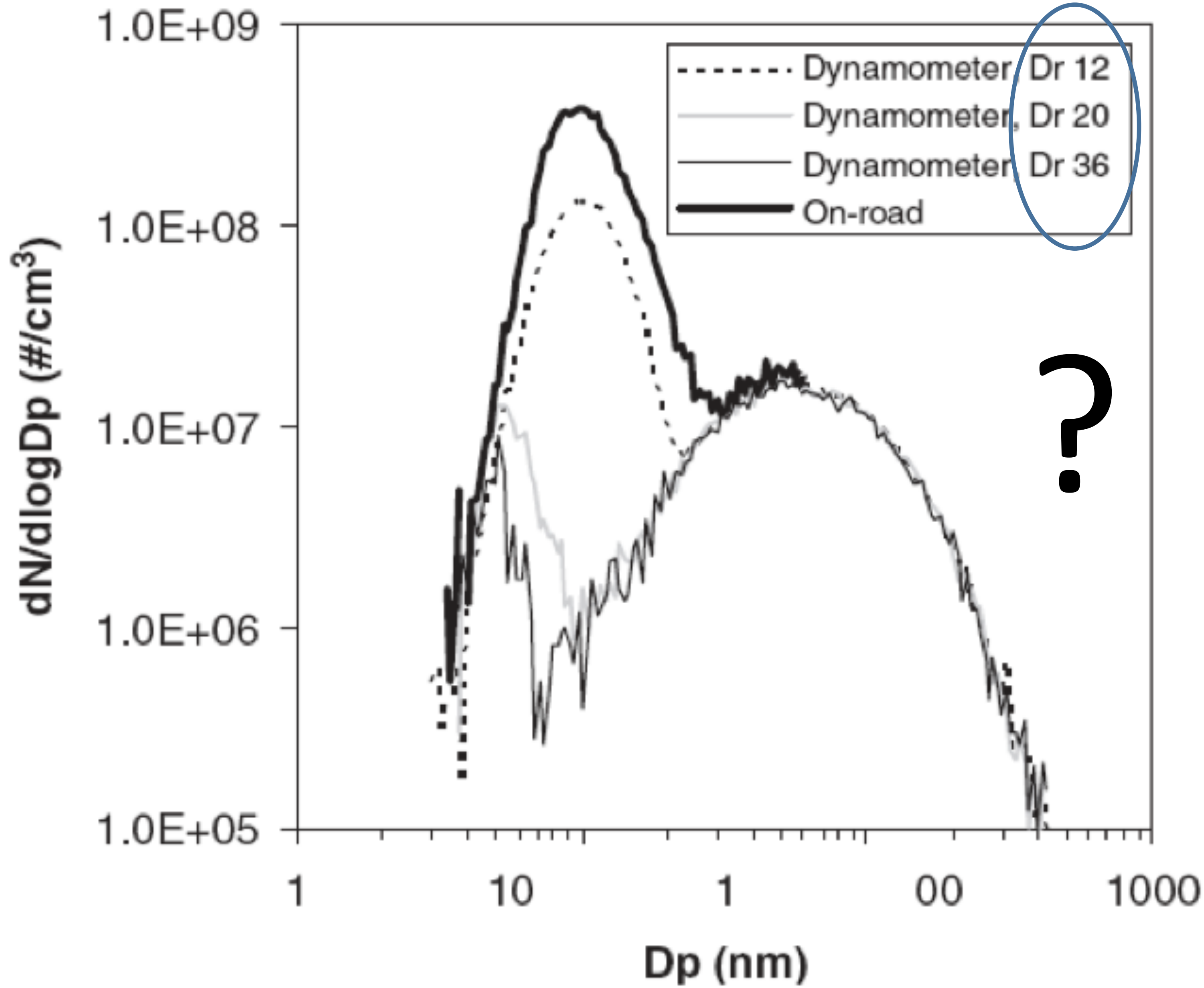
In-Lab Dilution



- Operate under well-controlled conditions
- Widely used for regulatory purposes because tests are …eatable.

Laboratory emission measurements may differ considerably from on-road emissions depending on chosen dilution parameters.

…*pheric Environment 40* (16), 2893-2901.


1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
dN/dlogDp (#/cm³)
Dynamometer, Dr 12
Dynamometer, Dr 20
Dynamometer, Dr 36
On-road
?
1
10
1
00
1000
Dp (nm)

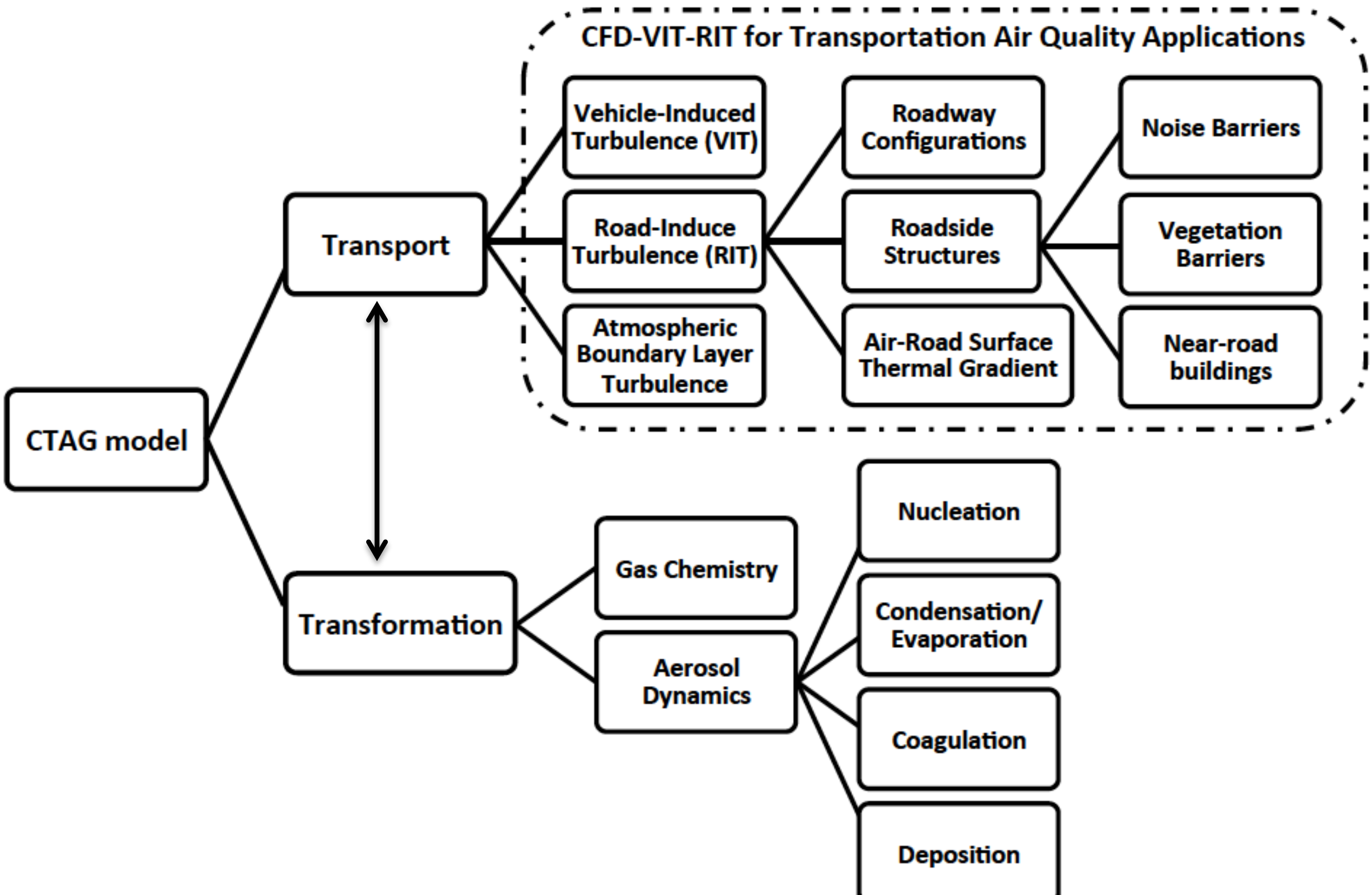
Objectives

- Characterize the aerodynamic properties of lab dilution sampling systems
- Compare different lab dilution sampling systems
- Compare lab systems with atmospheric sampling systems
- Improve scientific understanding and assist lab sampling systems designs

Approach

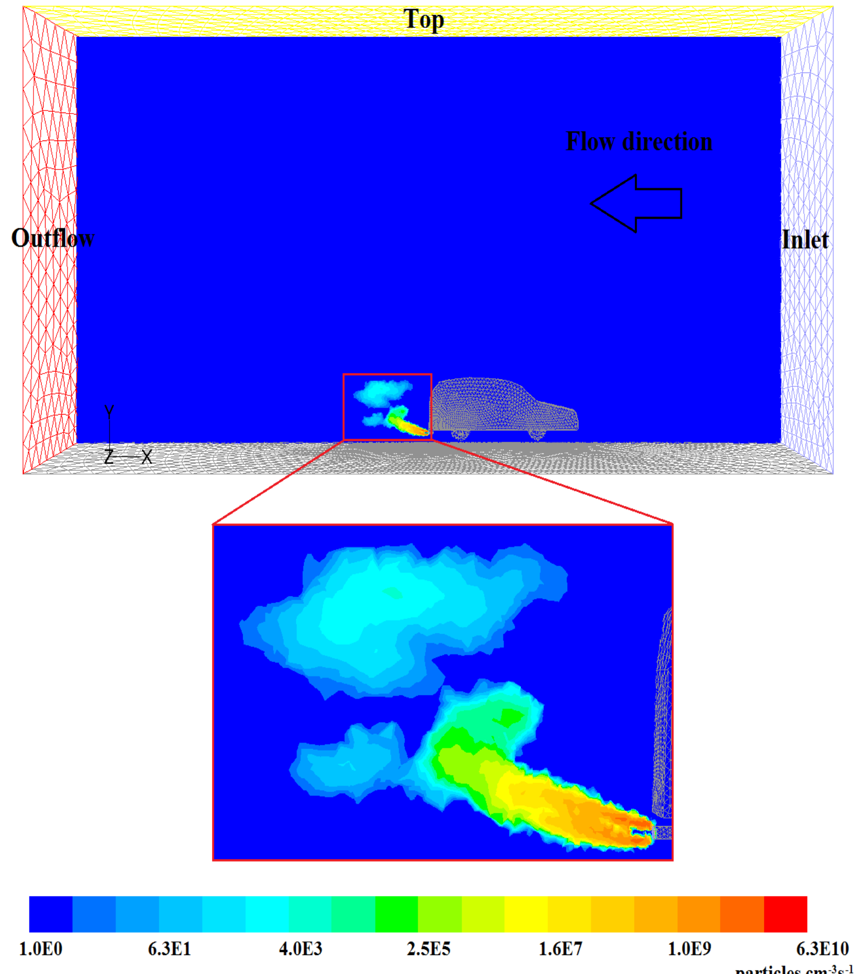
- Modeling analysis of experimental data
  - CMU: Different lab systems
  - Finland: Lab and atmospheric systems
- The modeling tool has to be capable of resolving the complex interactions of turbulent mixing and aerosol dynamics

***C**omprehensive **T**urbulent **A**erosol dynamics and **G**as chemistry (**CTAG**) model*

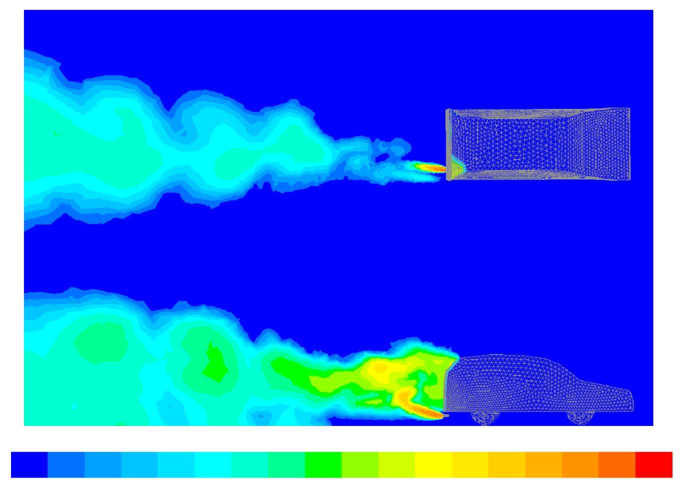


Wang and Zhang (2012) Atmospheric Environment 59: 284-293

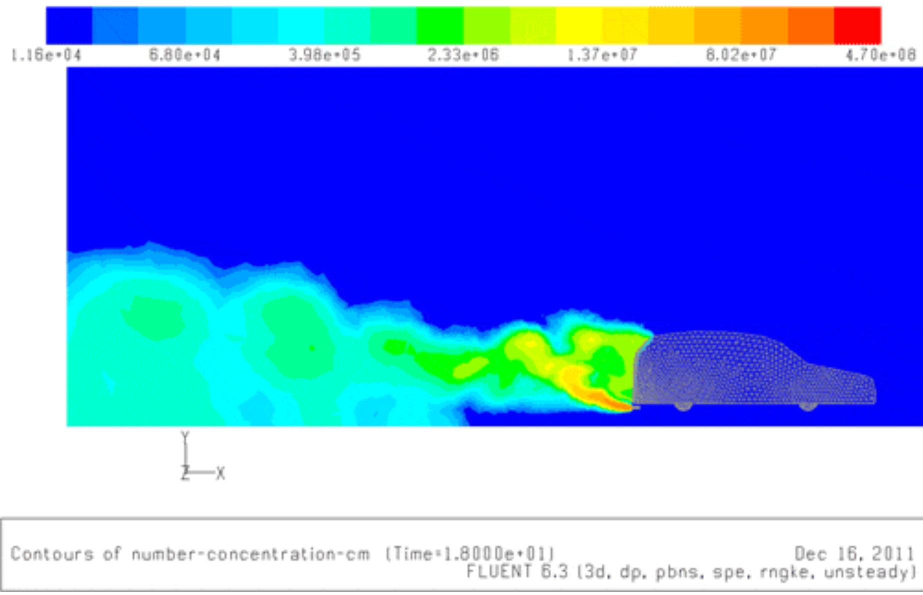
Aerosol dynamics in individual diluting diesel plumes

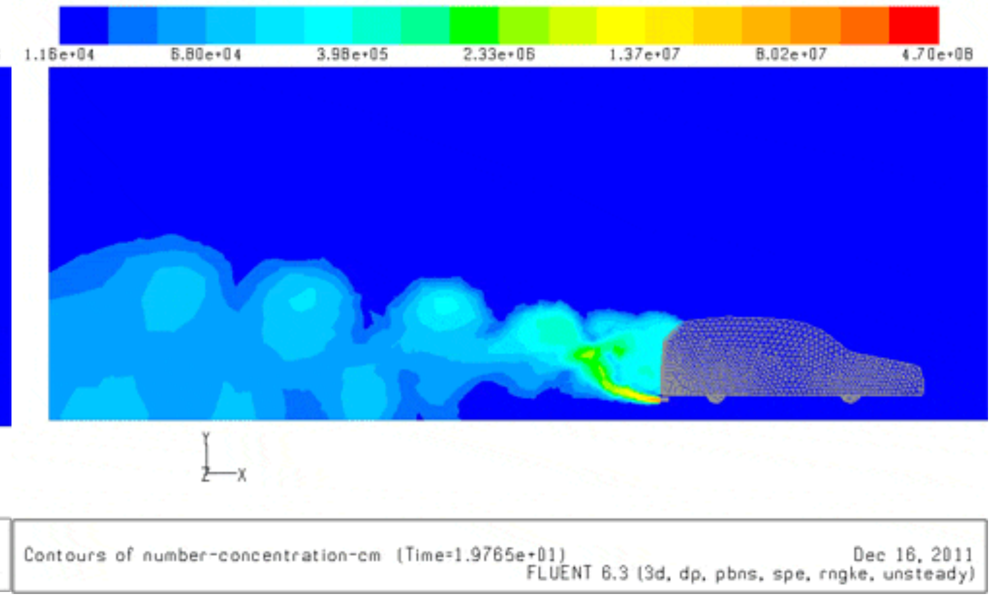


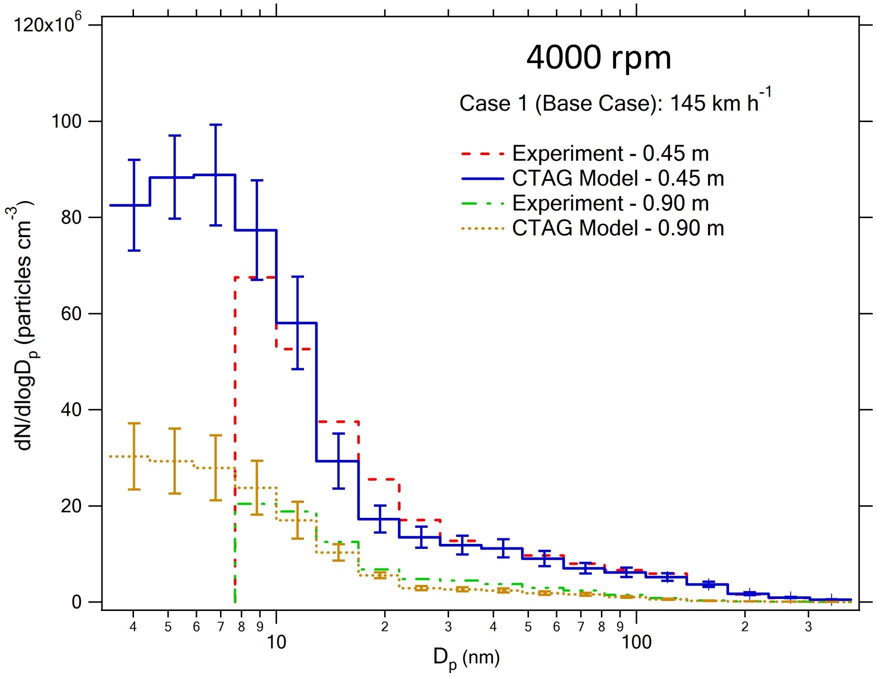
Nucleation rate for Case 1: 148 km h^{-1}, 4000 rpm

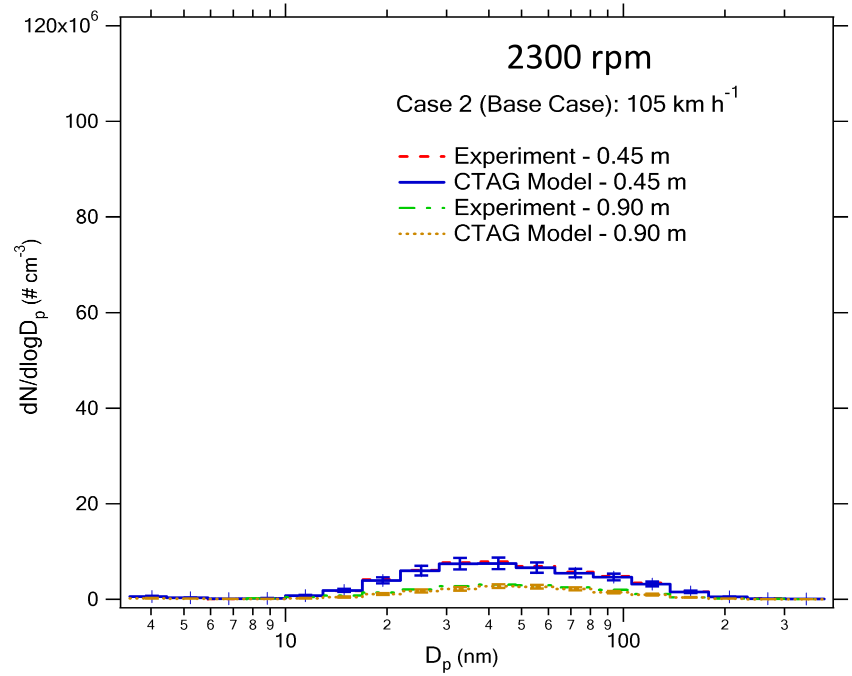


Aerosol number concentration for Case 1: 148 km h^{-1}, 4000 rpm

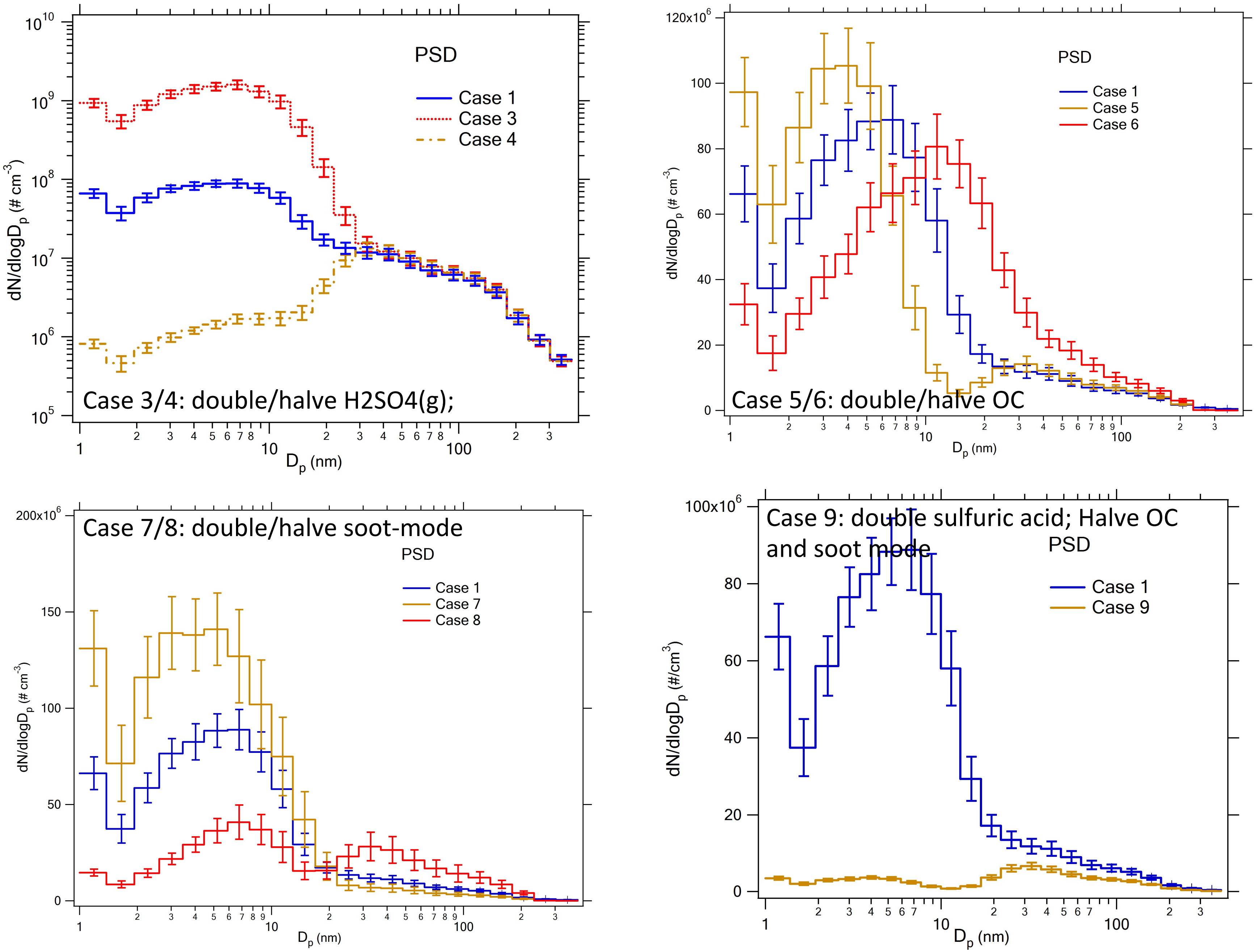




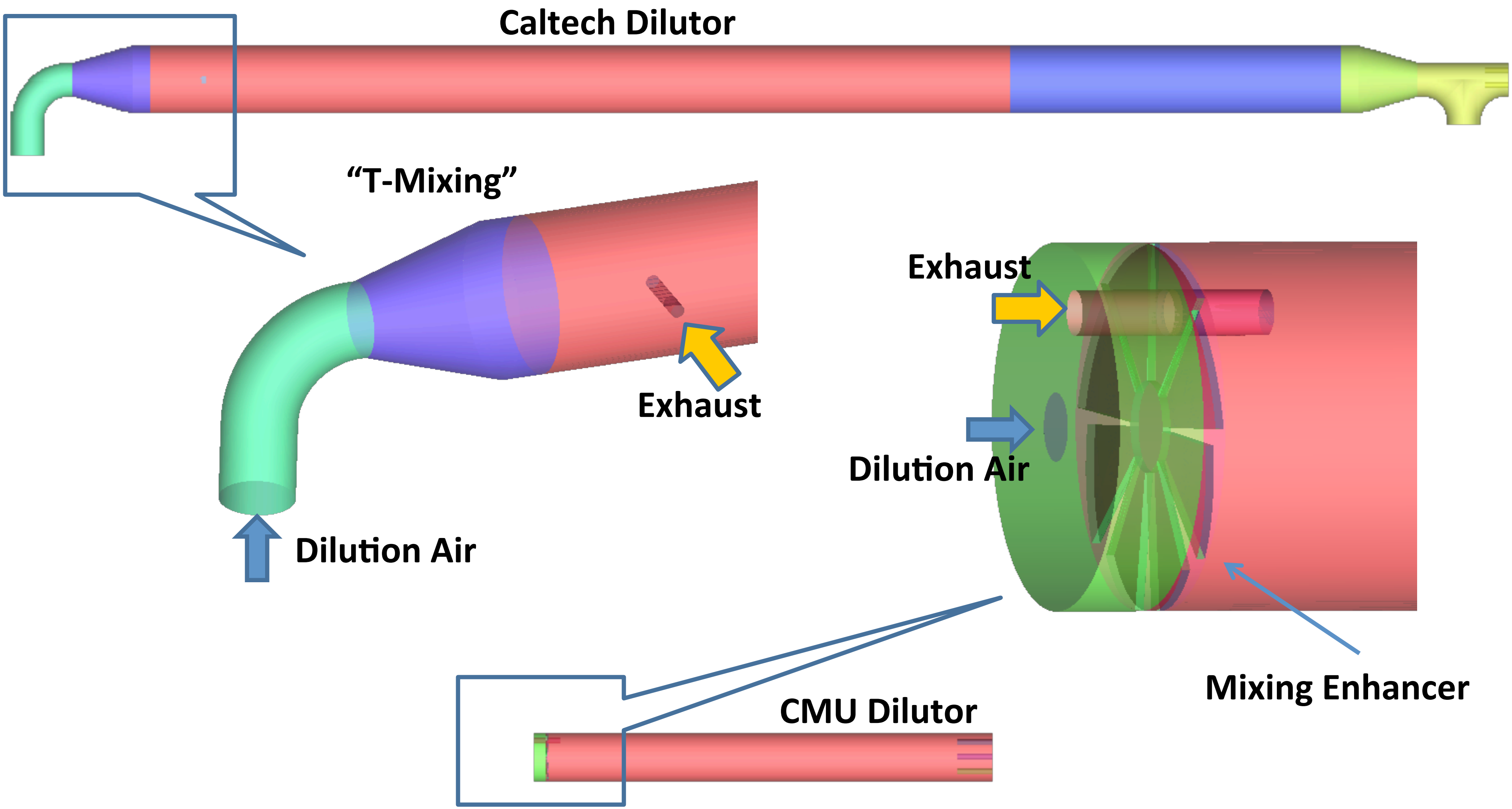




Wang and Zhang (2012) Atmospheric Environment 59: 284-293

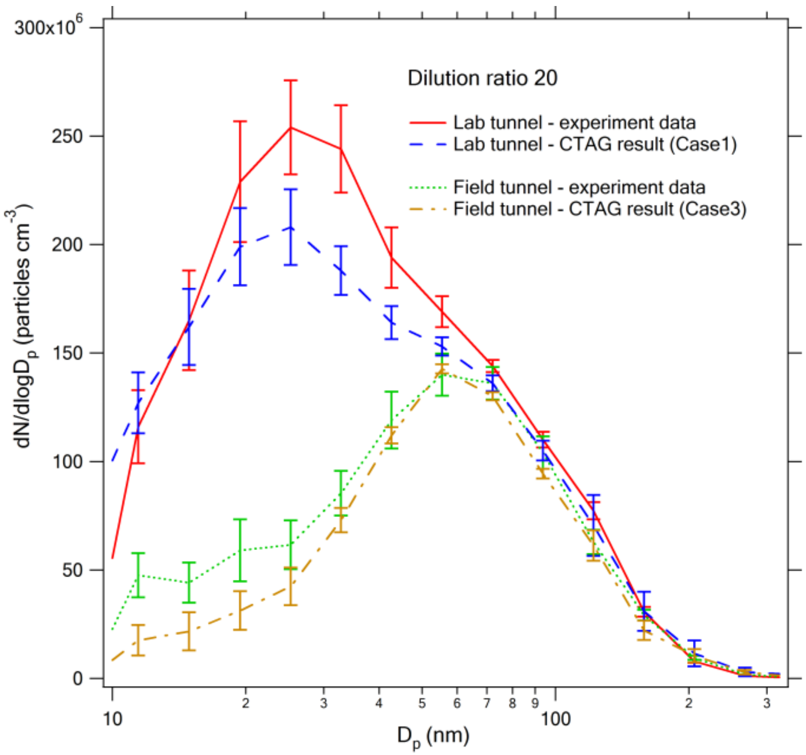

PSD
Case 1
Case 3
Case 4
Case 3/4: double/halve H2SO4(g);
dN/dlogDp (# cm-3)
Dp (nm)
PSD
Case 1
Case 5
Case 6
Case 5/6: double/halve OC
Case 7/8: double/halve soot-mode
PSD
Case 1
Case 7
Case 8
Case 9: double sulfuric acid; Halve OC and soot mode
PSD
Case 1
Case 9
dN/dlogDp (#/cm3)

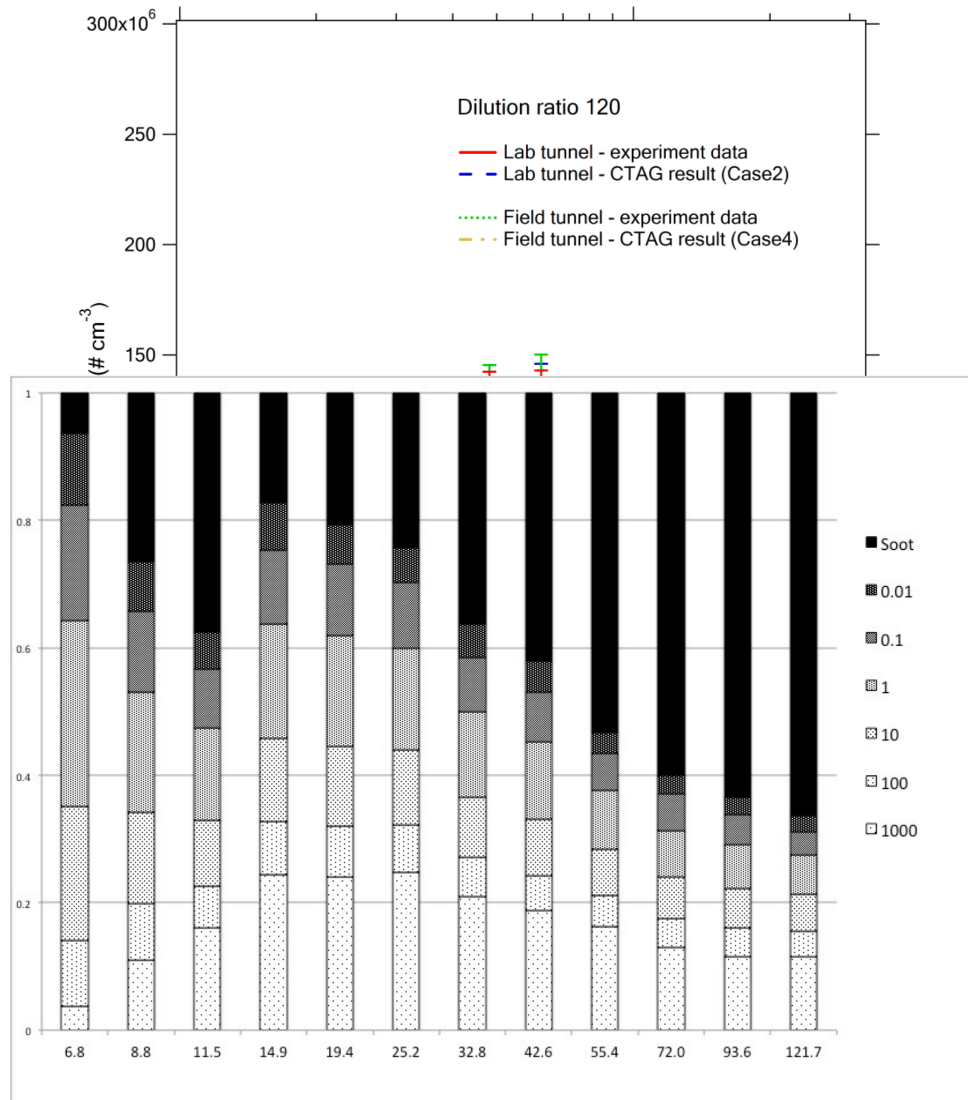
Dilutor Geometry



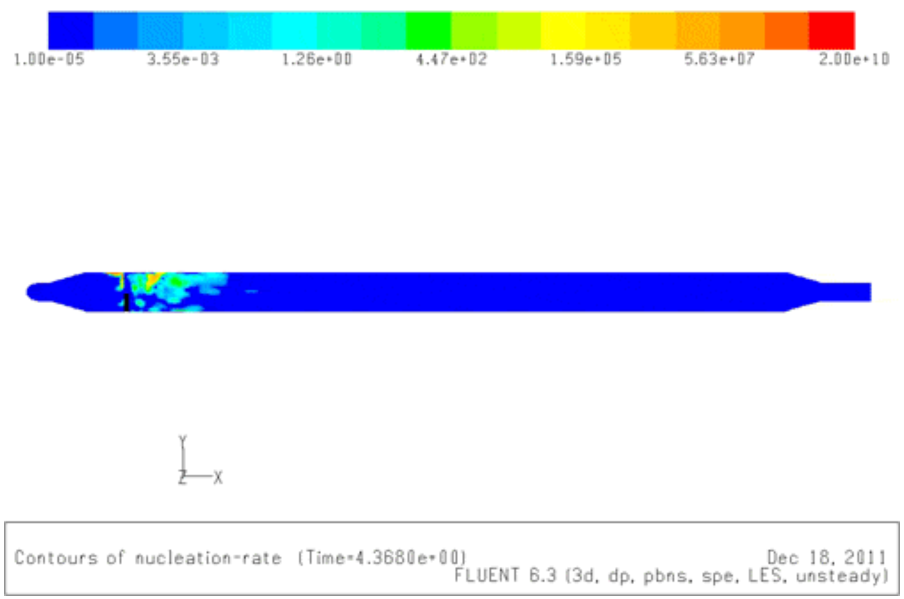
Wang et al. (2013) ES&T, 47:889-898

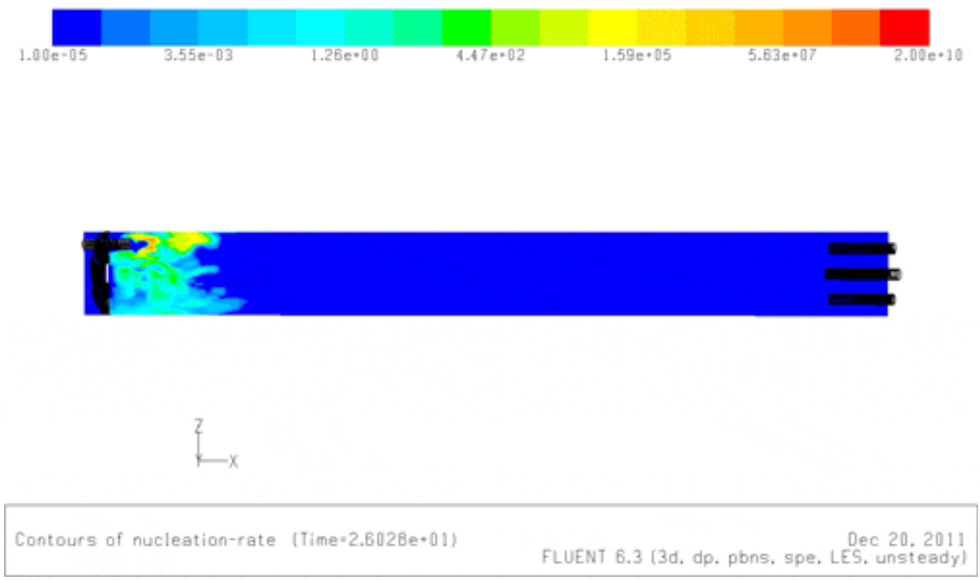
Predicted vs. Measured Particle Size Distributions

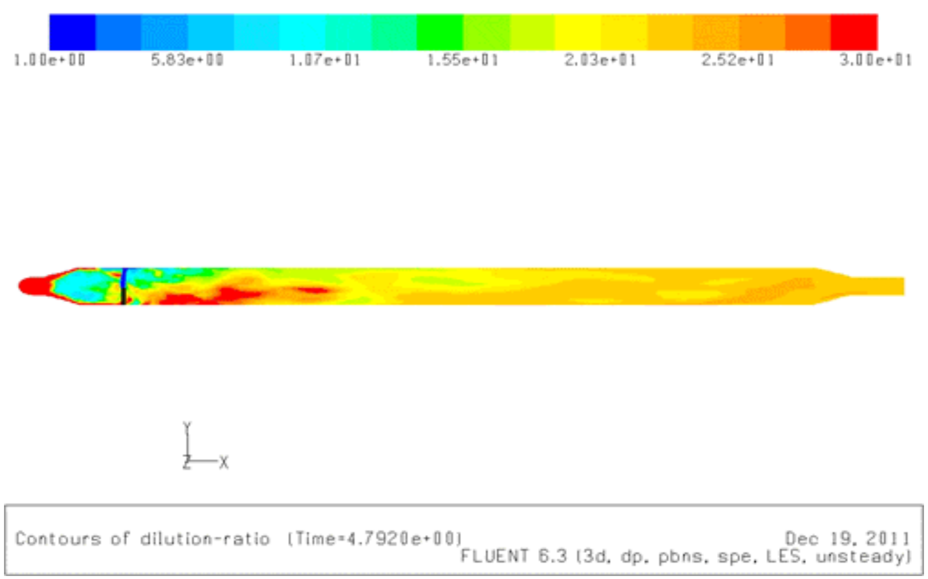


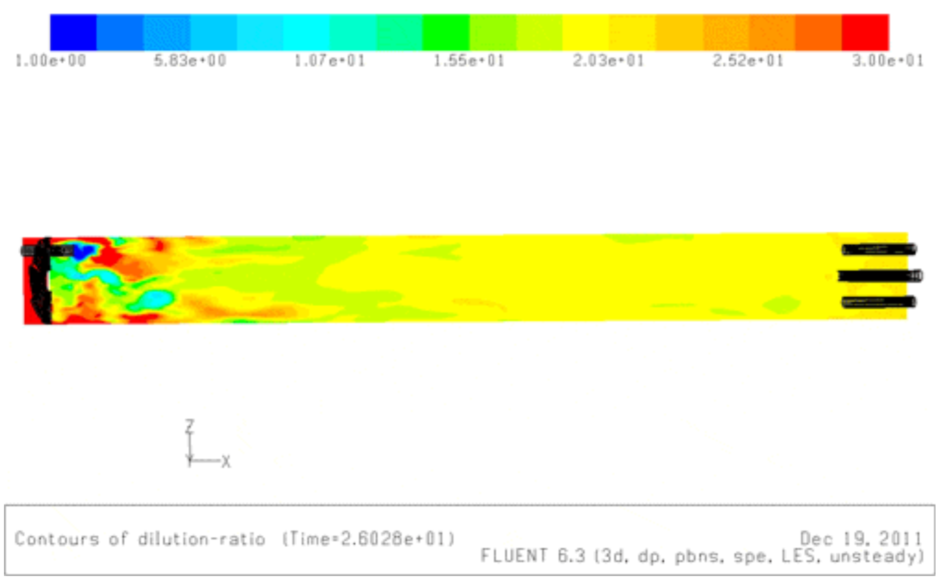


Wang et al. (2013) Environmental Science and Technology









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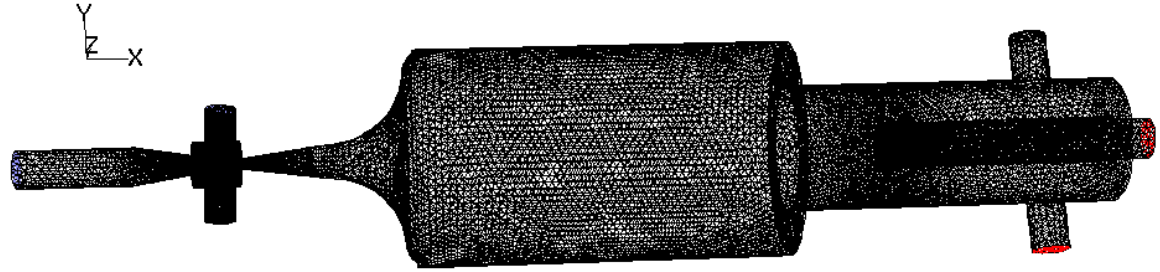
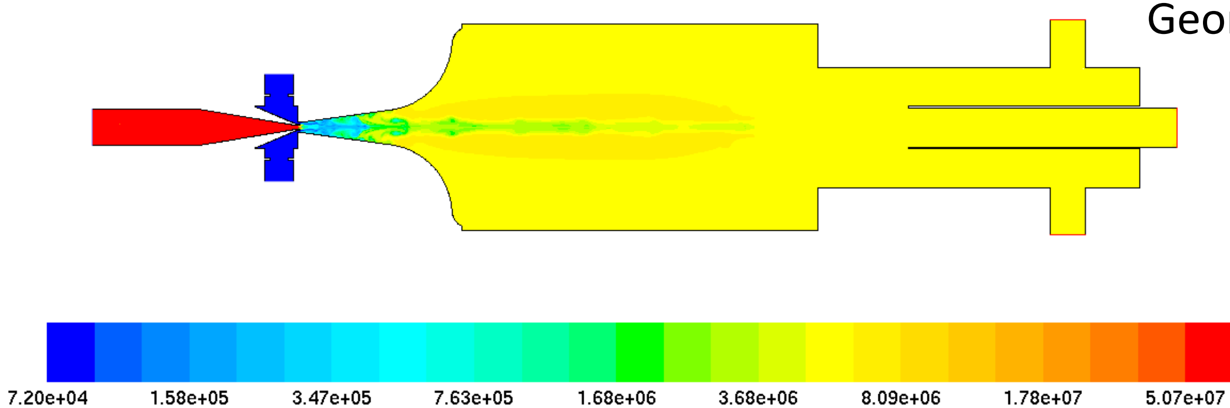
Ejector diluter

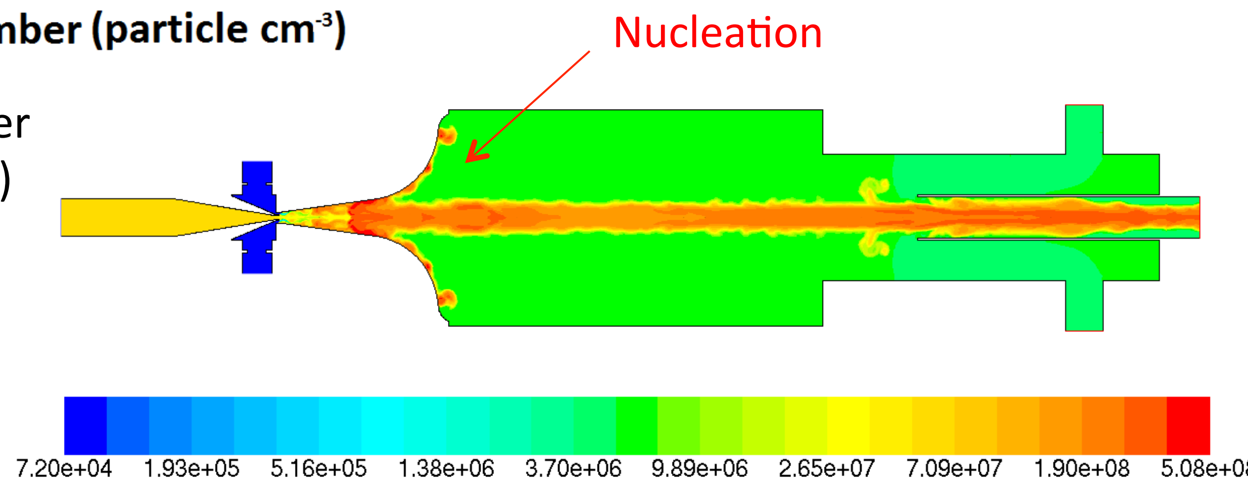


Geometry of the ejector diluter



PNC at low Mach Number (particle cm^{-3})

PNC distribution inside the diluter under low Mach Number (<1.0)



PNC at high Mach Number (particle cm^{-3})

PNC distribution inside the diluter under high Mach Number (>1.0)

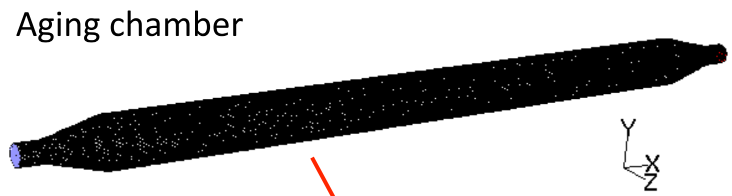
Manuscript in progress

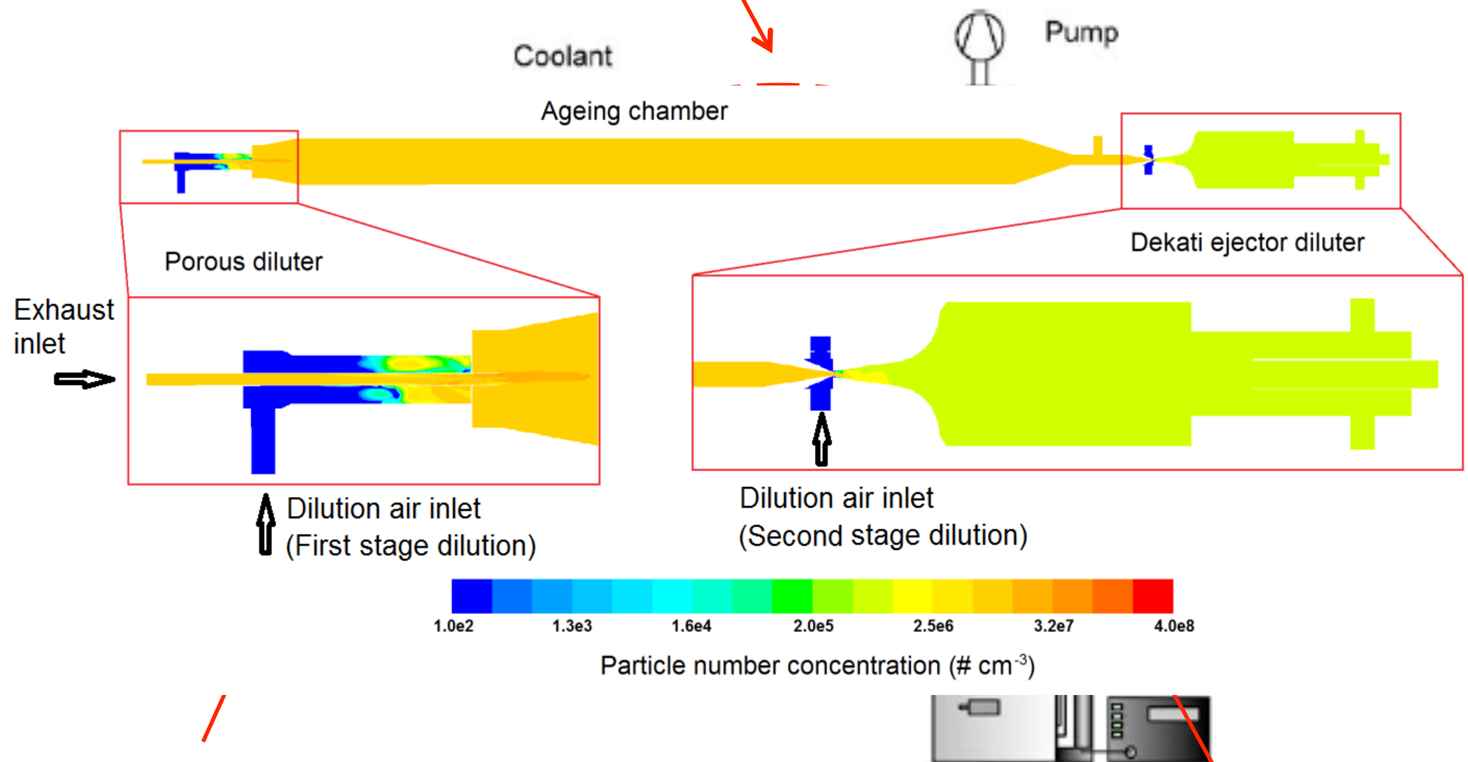
Rotating Disk Dilutor

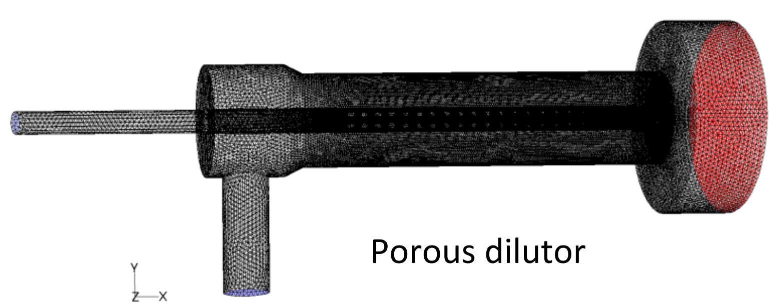
http://www.youtube.com/watch?v=-B1Nu2CUb14

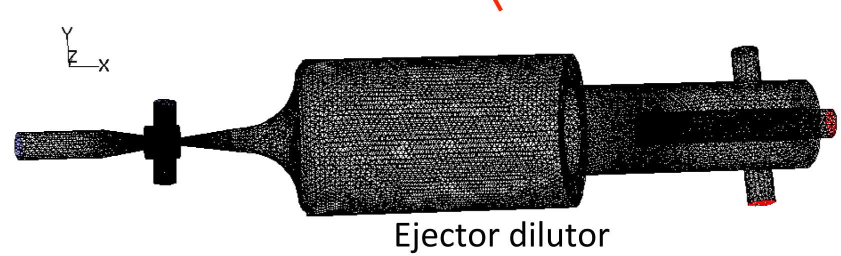
Sampling train for the "Particulates" research program of EU

Manuscript in progress

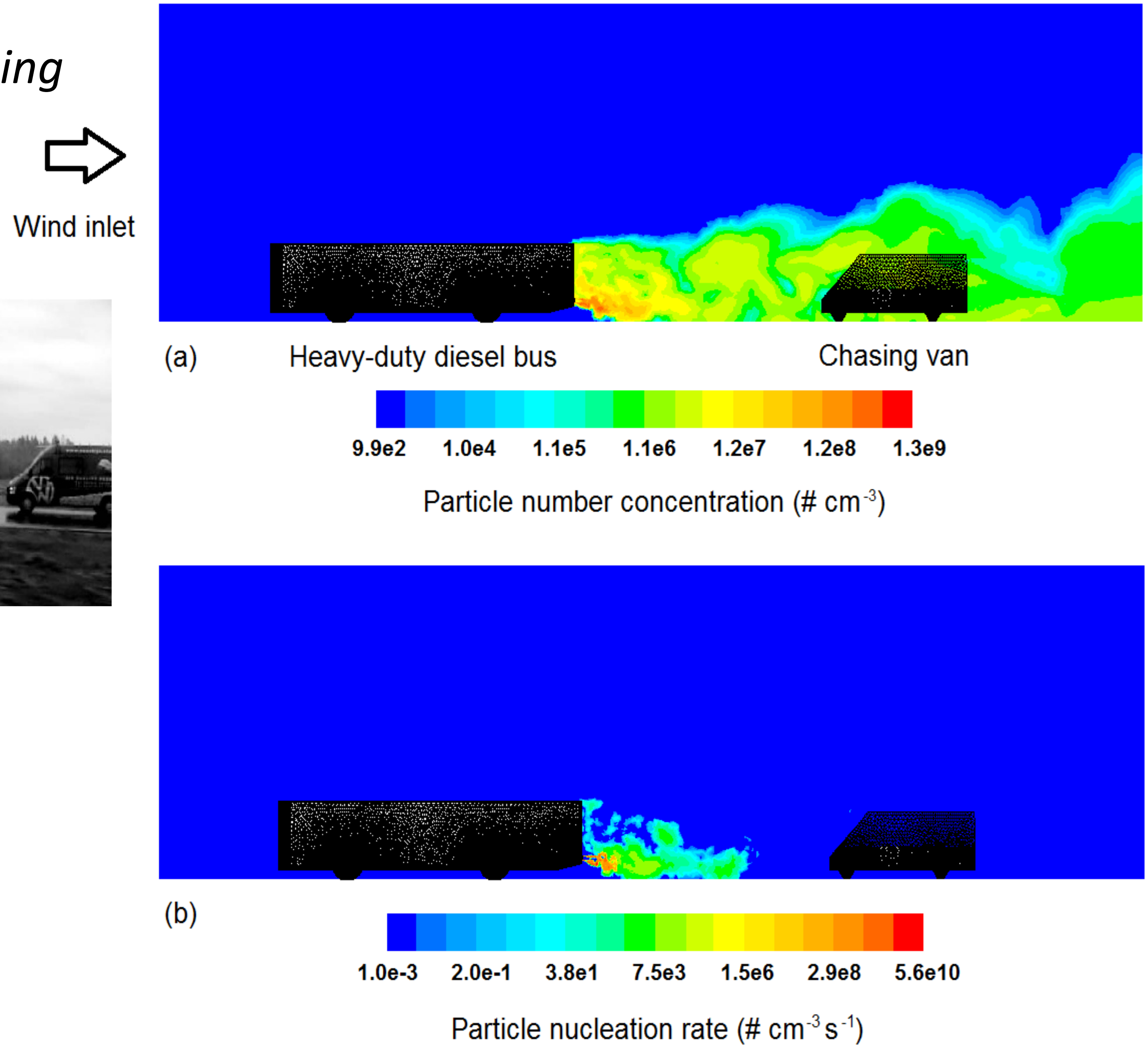








On-road Chasing



Manuscript in progress

Dilution Ratio vs Dilution Rate

- Dilution ratio is typically used to characterize dilution system, but it is inadequate to characterize the mixing process.
- We introduce another metric, dilution rate, at which the exhaust and dilution air are brought together at the molecular level
  – Represented by the scalar dissipation rate of exhaust

$$\varepsilon_{\xi} = C_{\phi} < {\xi'}^{2} > \frac{\varepsilon}{k}$$

Turbulent dissipation rate

Turbulent kinetic energy

Mixture variance

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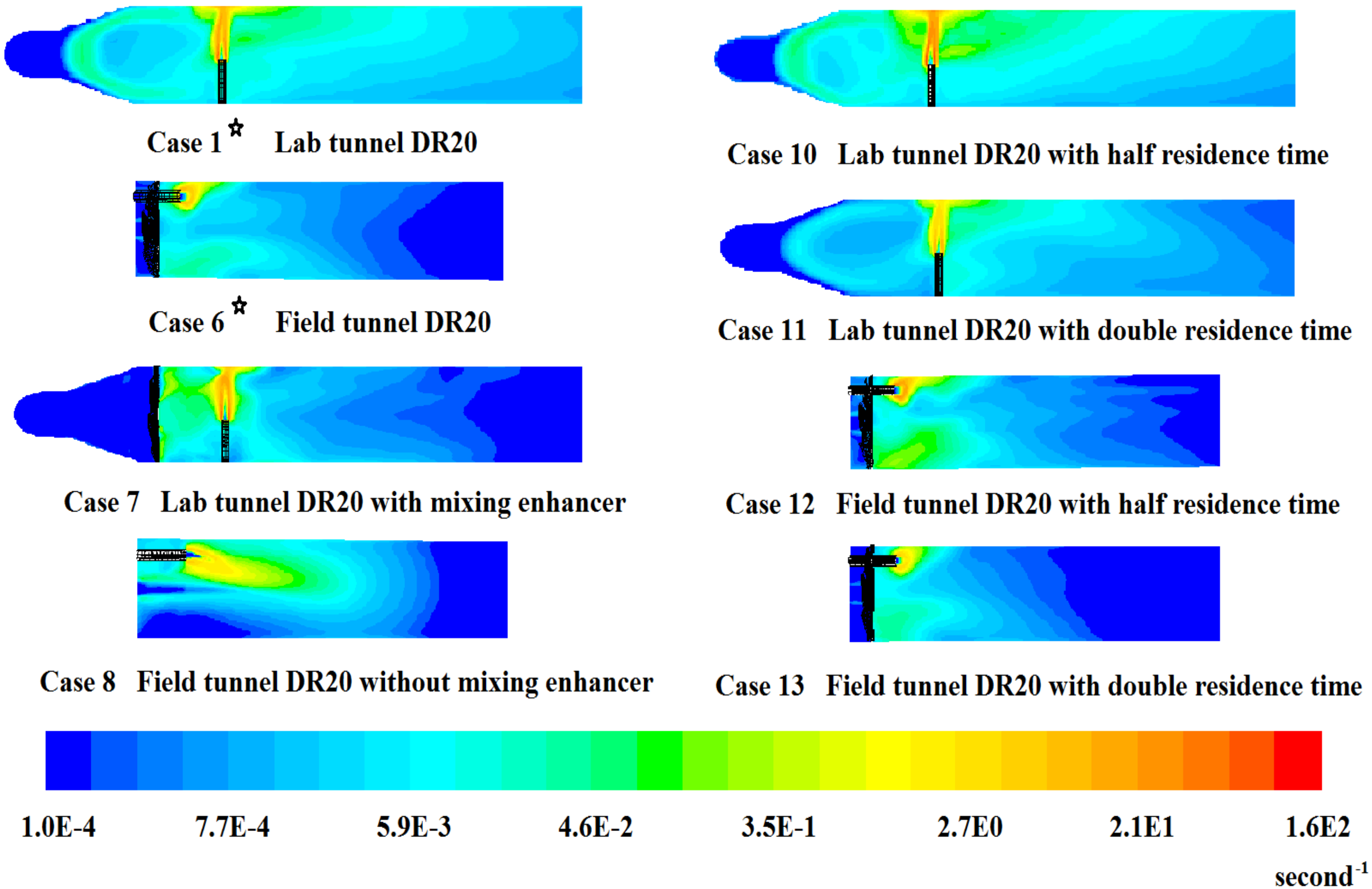
Time-averaged Dilution Rate



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Remarks

- This study marked the first quantitative investigation of aerodynamics properties of dilution sampling system.
- In general, both dilution rates and dilution ratios need to be quantified to characterize the aerodynamic properties in lab and atmospheric dilution sampling systems.
- Dilution rate profiles of any dilution sampling systems can be *reliably* predicted by CTAG using sampling system geometric configurations, exhaust and dilution temperature and air flow rates.
  - Turbulent flow modeling (computationally heavy but relatively mature) WITHOUT aerosol dynamics

Implications

- CTAG can be used to simulate the entire sampling train for the laboratory system
  - Different components
  - Particle losses
  - PM formation
  - …
- Bridge between lab system and atmospheric system
- Potentially valuable in
  - Quantify the uncertainties in current sampling systems
  - Design new sampling systems
  - …

CTAG-related publications

Wang, Y; Yang, B; Lipsky, E; Robinson, A; Zhang, K. M. (2013) Analyses of turbulent flow fields and aerosol dynamics of diesel engine exhaust inside two dilution sampling tunnels using the CTAG model. *Environmental Science & Technology*. 47(2): 889-898

Jonathan T. Steffens, David K. Heist, Steven G. Perry and K. Max Zhang. (2013) Modeling the effects of a solid barrier on pollutant dispersion under various atmospheric stability conditions. *Atmospheric Environment* 69: 76-85

Wang, Y., Nguyen, M., Jonathan, S., Tong, Z., Zhang, K., et al. (2013) Modeling multi-scale aerosol dynamics and micro-environmental air quality near a large highway intersection using the CTAG model. *Science of the Total Environmen*t 443: 375-386,

Wang, Y. and Zhang, K.M Coupled and aerosol dynamics modeling of vehicle exhaust plumes using the CTAG model. (2012) *Atmospheric Environment* 59: 284-293

Steffens, J. T., Wang, Y. and Zhang, K. M., (2012) Exploration of effects of a vegetation barrier on the dispersion of pollutants in a near road environment. *Atmospheric Environment*, 50: 120-128

Tong, Z., Wang, Y., Patel, M., Kinney, P., Chillrud, S. and Zhang, K. M. (2012) Modeling spatial variations of black carbon particles in an urban highway-buildings environment, *Environmental Science & Technology* 46 (1): 312-319

Wang, Y. McDonald-Buller, E., Denbleyker, A., Allen, D. and Zhang, K.M. (2011) Modeling chemical transformation of nitrogen oxides near roadways, *Atmospheric Environment* 45(1): 43-52

Wang, Y. and Zhang, K.M. (2009) Modeling near-road air quality using a computational fluid dynamics (CFD) model, CFD-VIT-RIT. *Environmental Science & Technology*, 43: 7778-7783