Cornell University

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

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Acknowledgment

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

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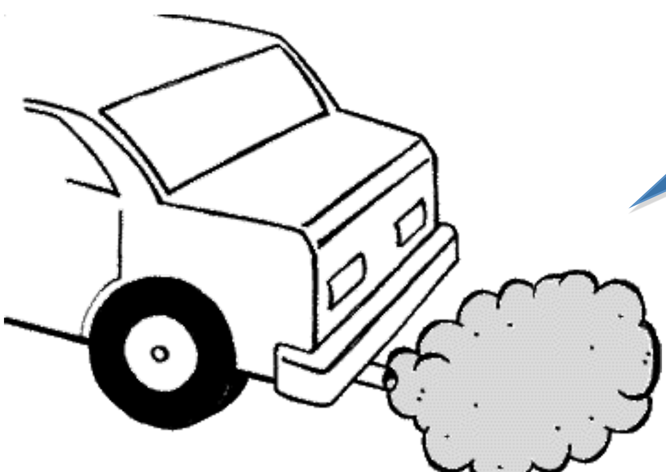
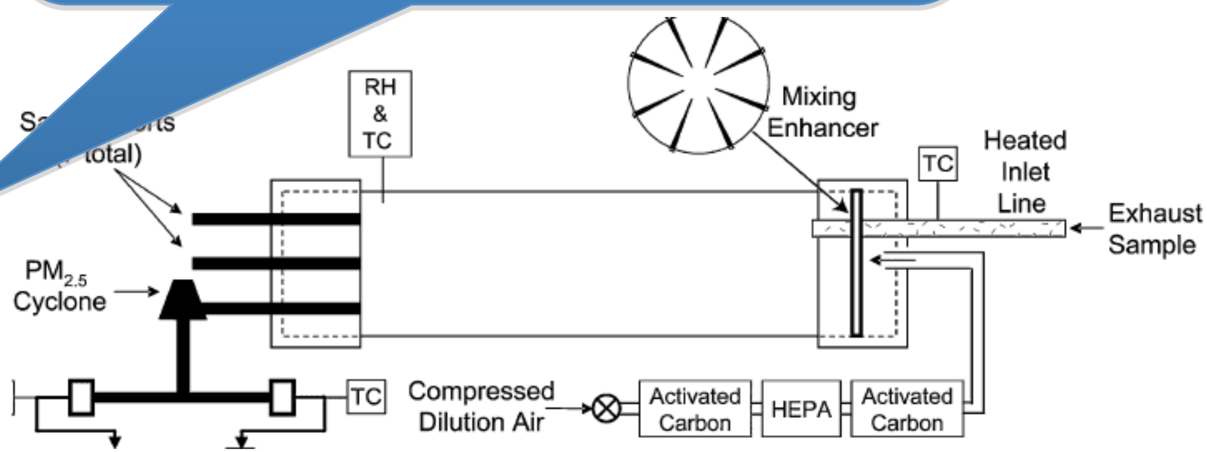
A Tale of Two "Reactors"

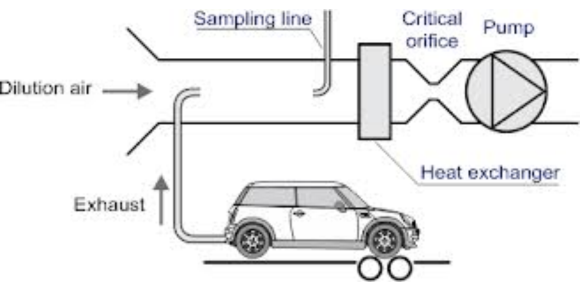
- Atmosphere and laboratory dilution tunnels can be regarded as "***turbulent reactors***":
  - cooling the exhaust
  - generating new p
  - changing the pro
- Same nature!

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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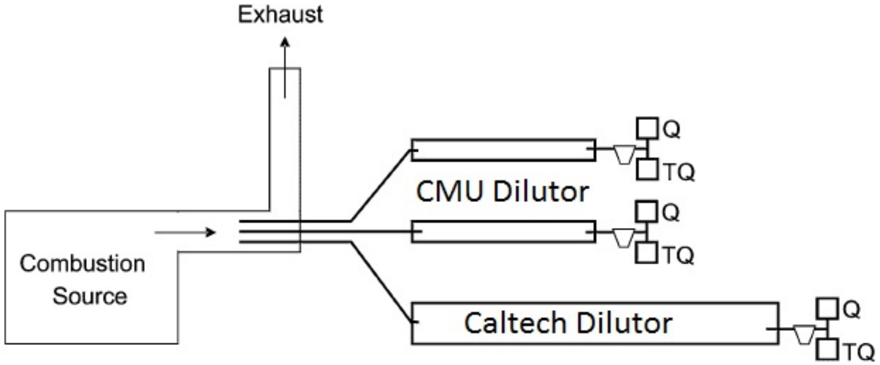
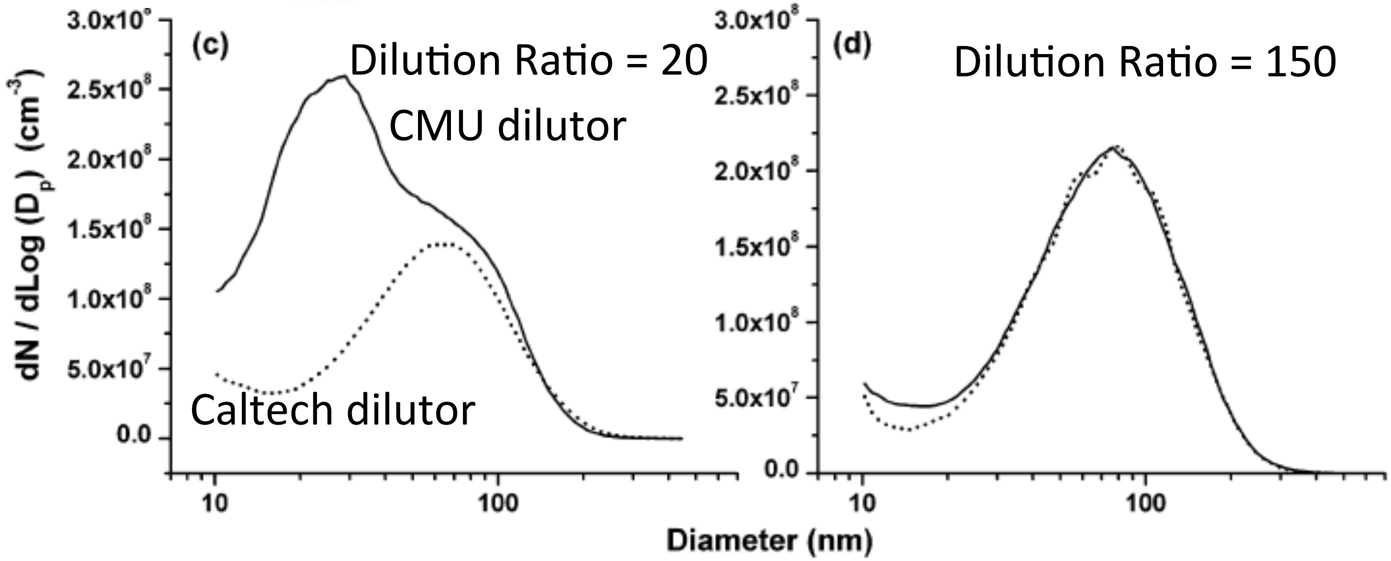
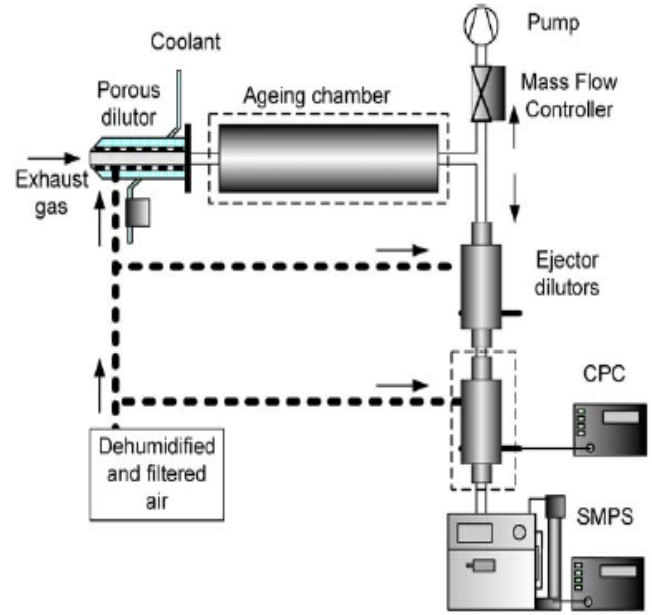




Dilution-corrected number size distributions measured during two diesel intercomparison experiments between the CMU dilutor (the dash line) and the Caltech dilutor (the solid line) (Lipsky and Robinson, 2005)

On-Road Chasing

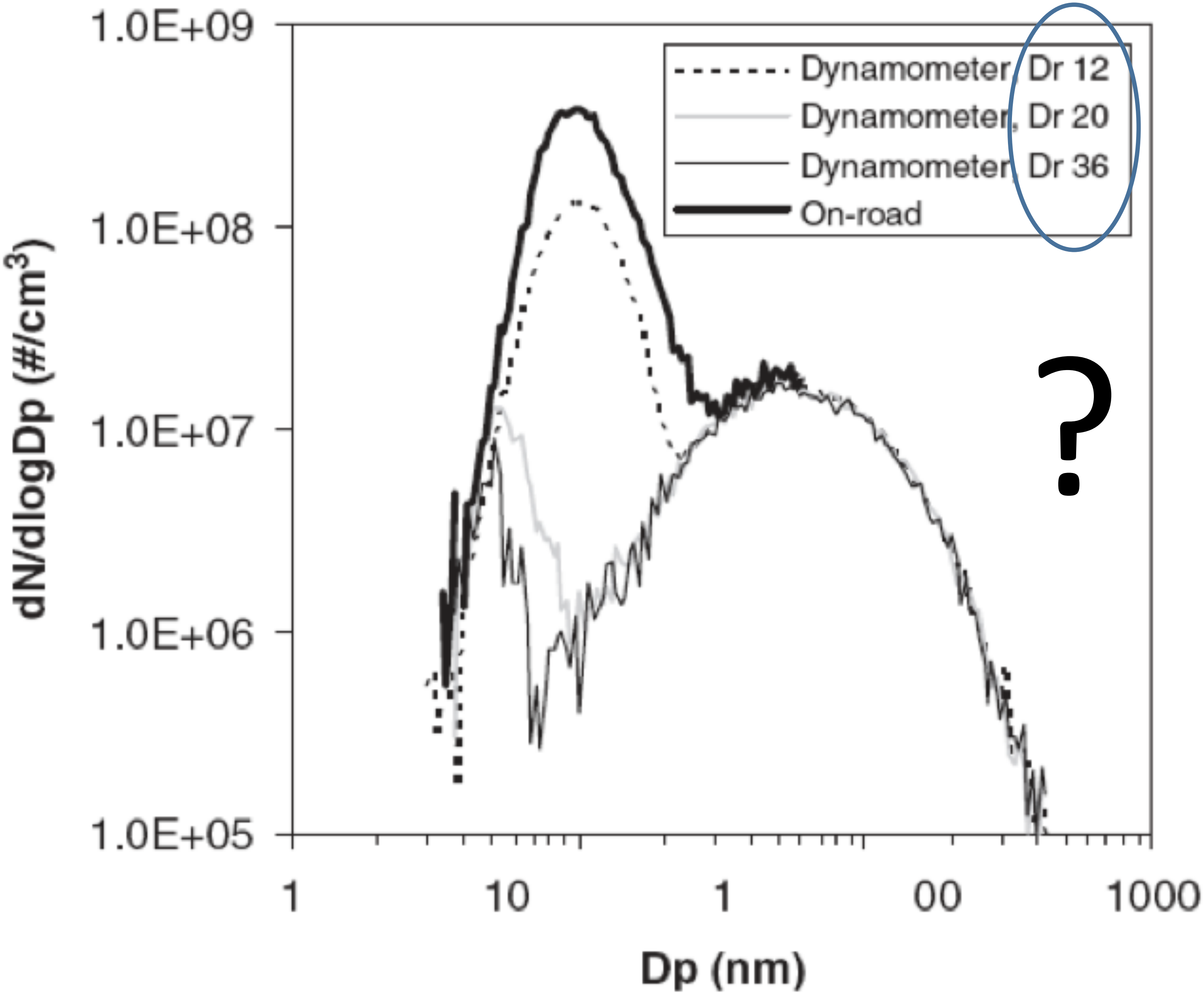
In-Lab Dilution



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

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

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)

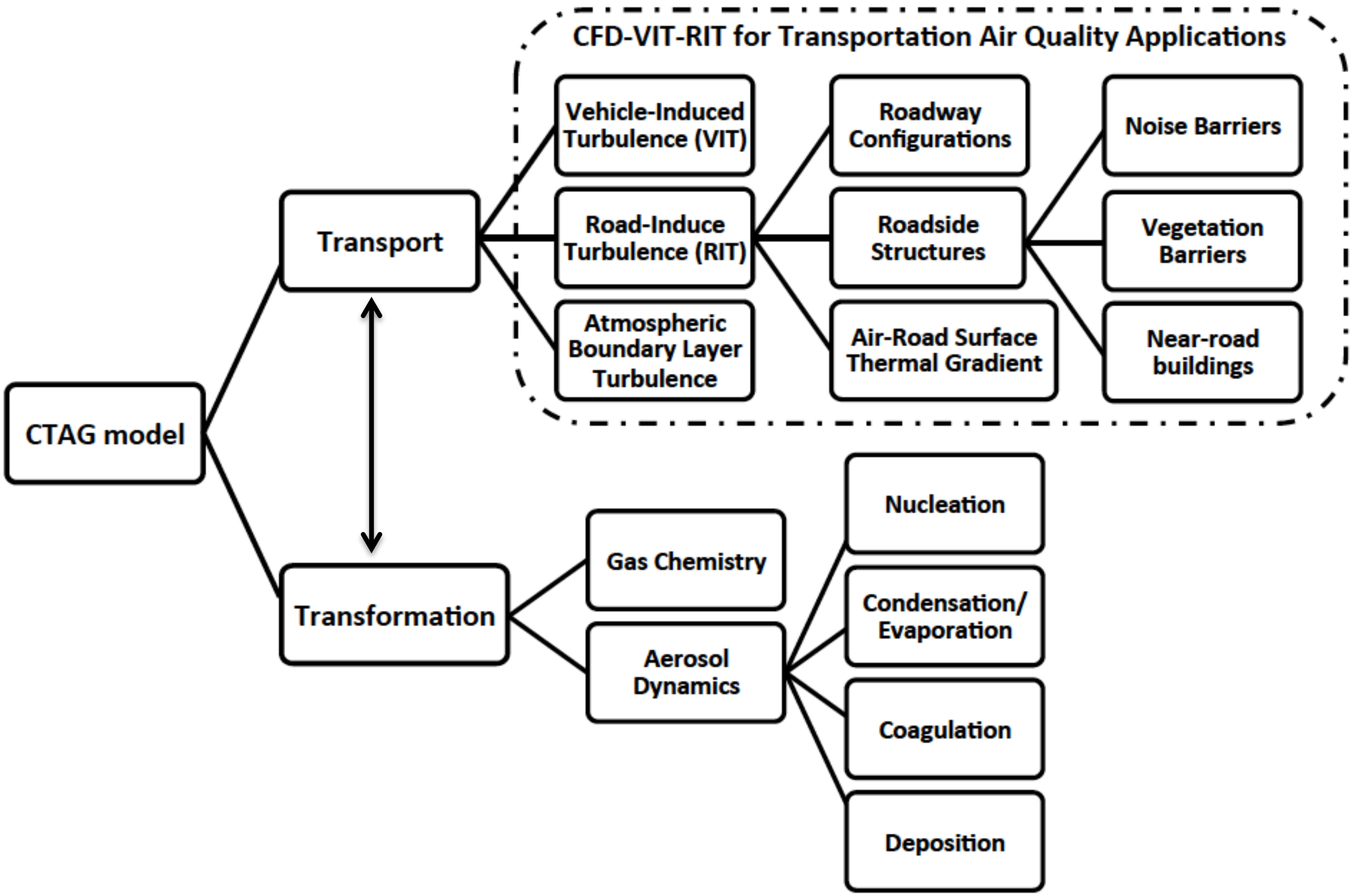
Objectives

- 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

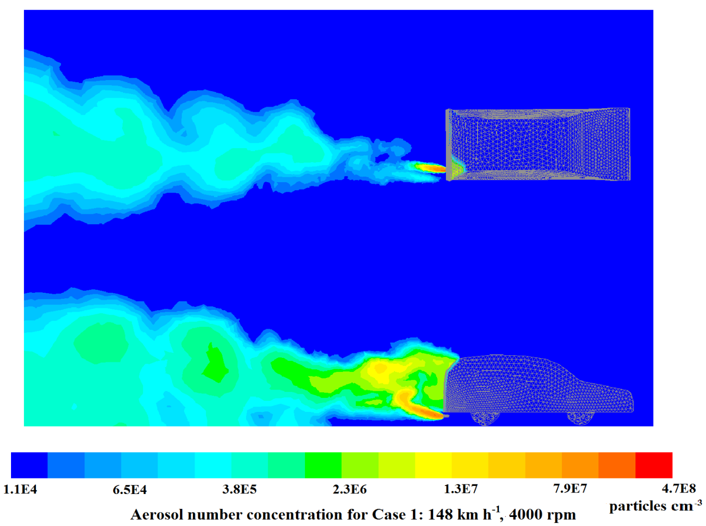
- Modeling analysis of experimental data
  - CMU: Different lab systems
  - Finland: Lab and atmospheric systems
- The modeling tool has to be capable of resolving the complex interactions of turbulent mixing and aerosol dynamics

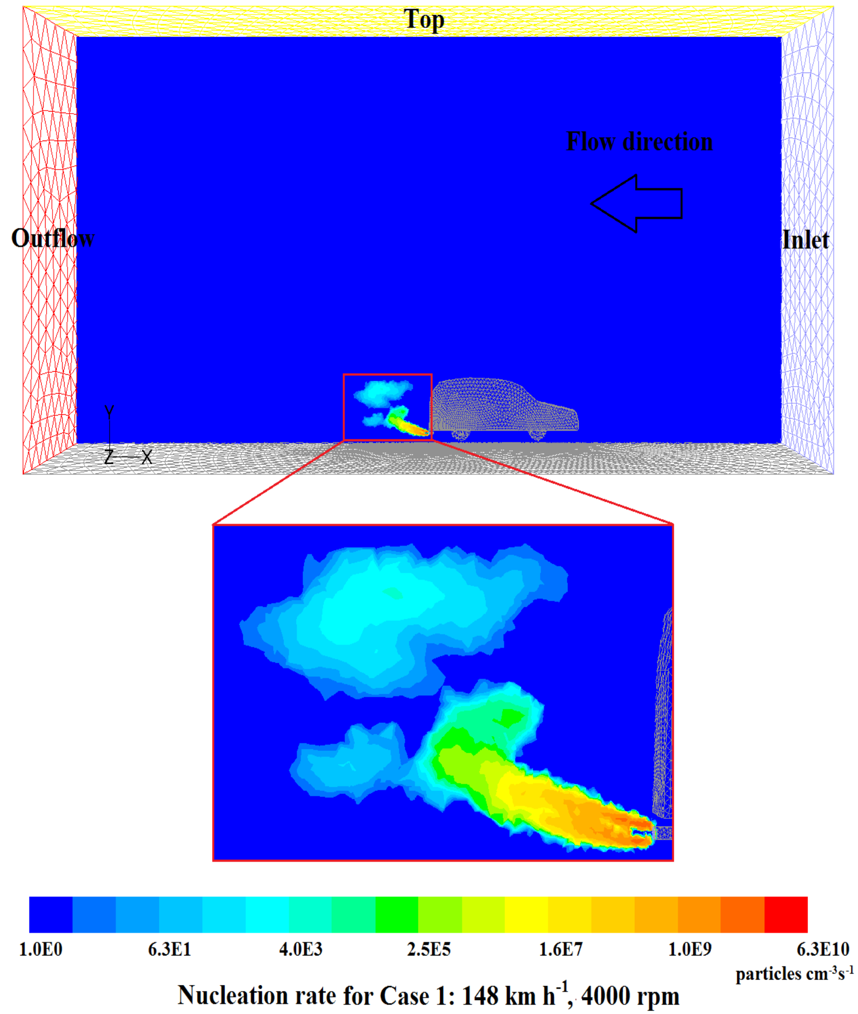
***C**omprehensive **T**urbulent **A**erosol dynamics and **G**as chemistry (**CTAG**) model*



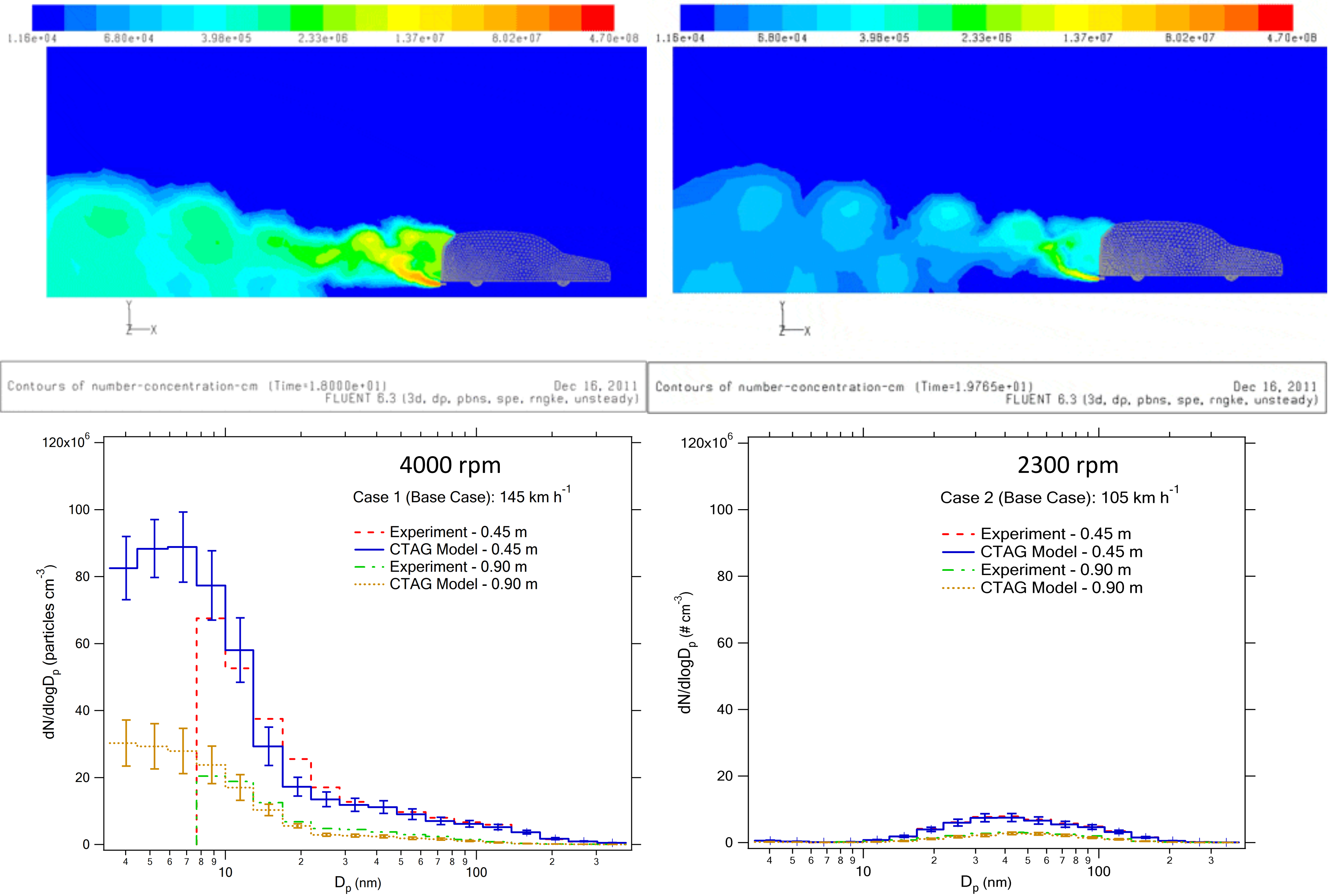
Wang and Zhang (2012) Atmospheric Environment 59: 284-293

Aerosol dynamics in individual diluting diesel plumes





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



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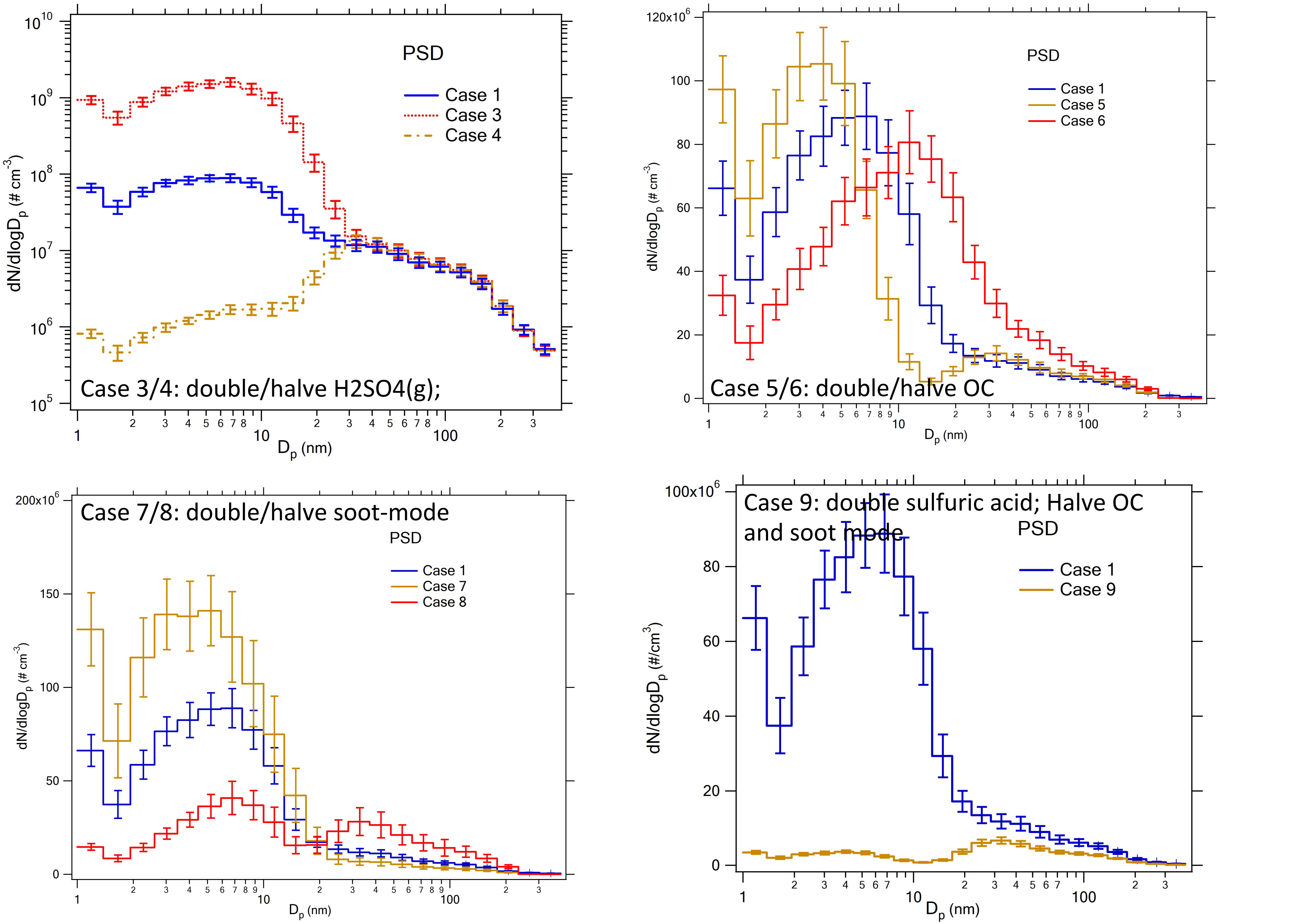
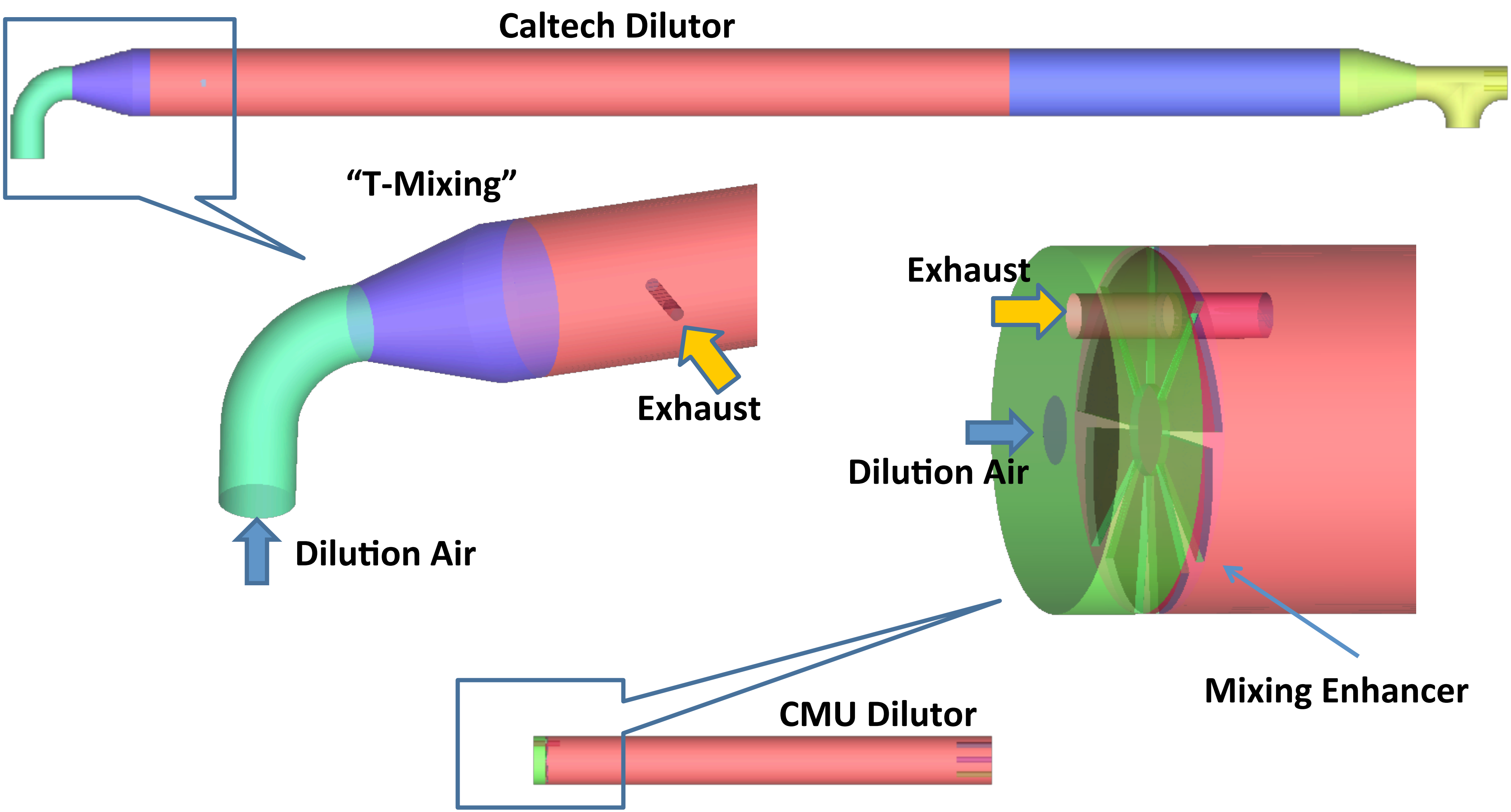


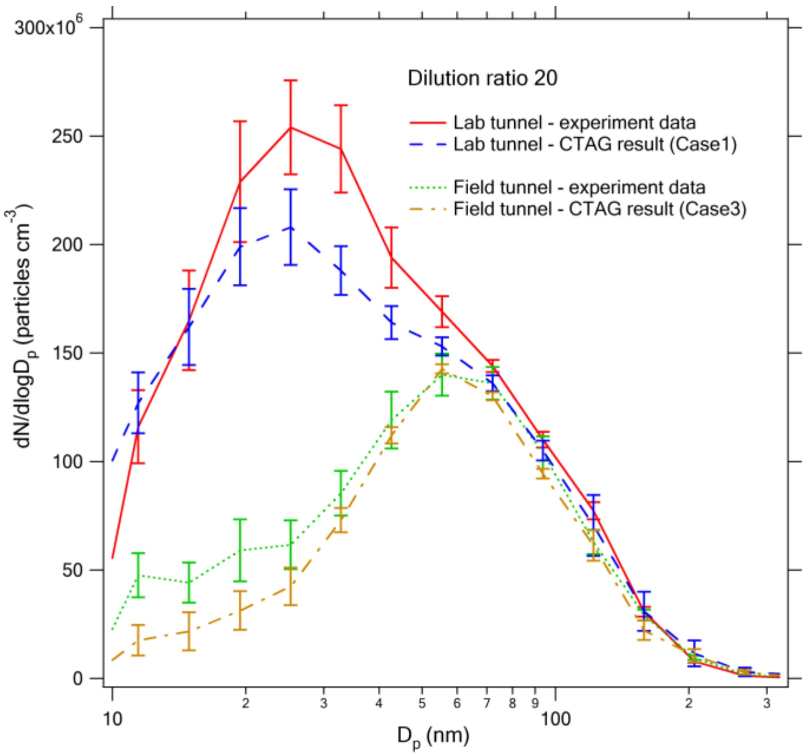
PSD
Case 1
Case 3
Case 4
Case 3/4: double/halve H2SO4(g);
dN/dlogDp (# cm-3)
Dp (nm)
PSD
Case 1
Case 5
Case 6
Case 5/6: double/halve OC
dN/dlogDp (# cm-3)
Dp (nm)
Case 7/8: double/halve soot-mode
PSD
Case 1
Case 7
Case 8
dN/dlogDp (# cm-3)
Dp (nm)
Case 9: double sulfuric acid; Halve OC
and soot mode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

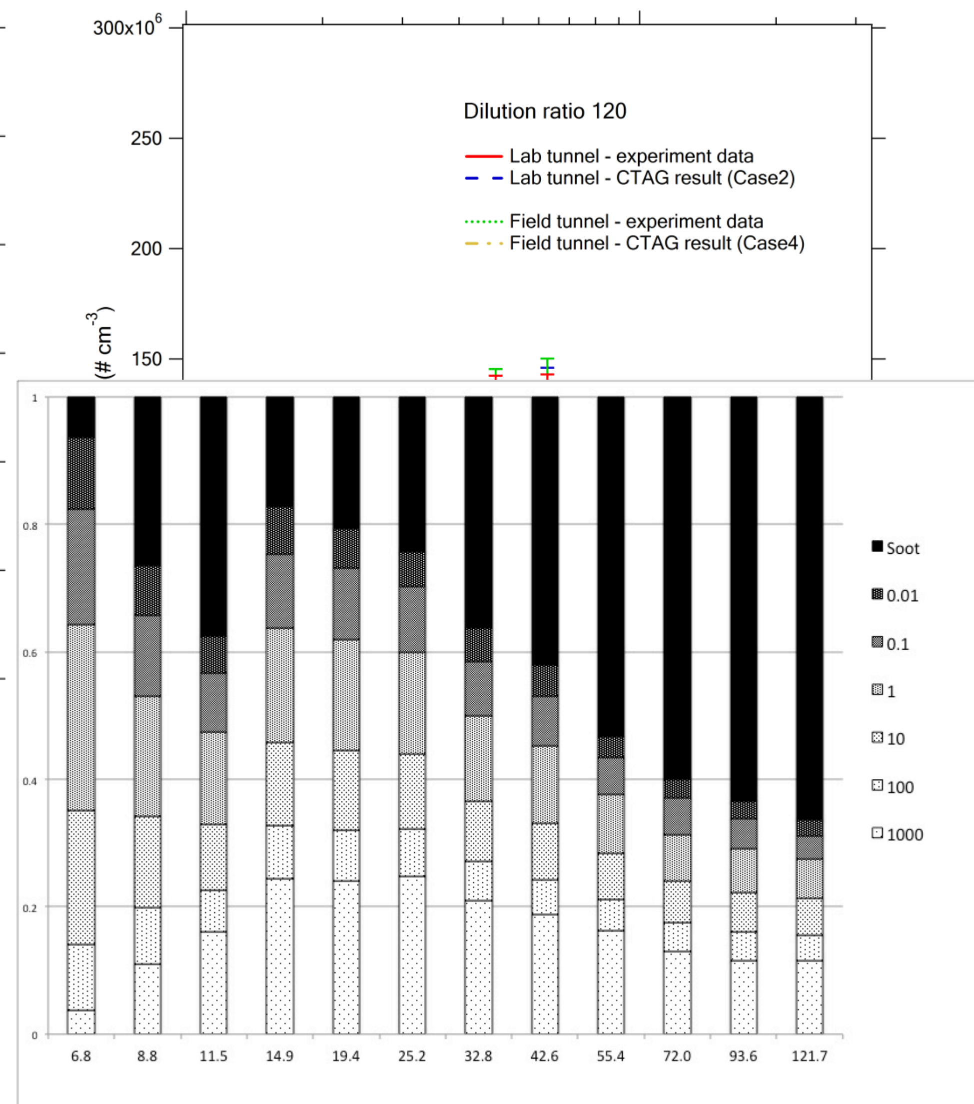
Dilutor Geometry



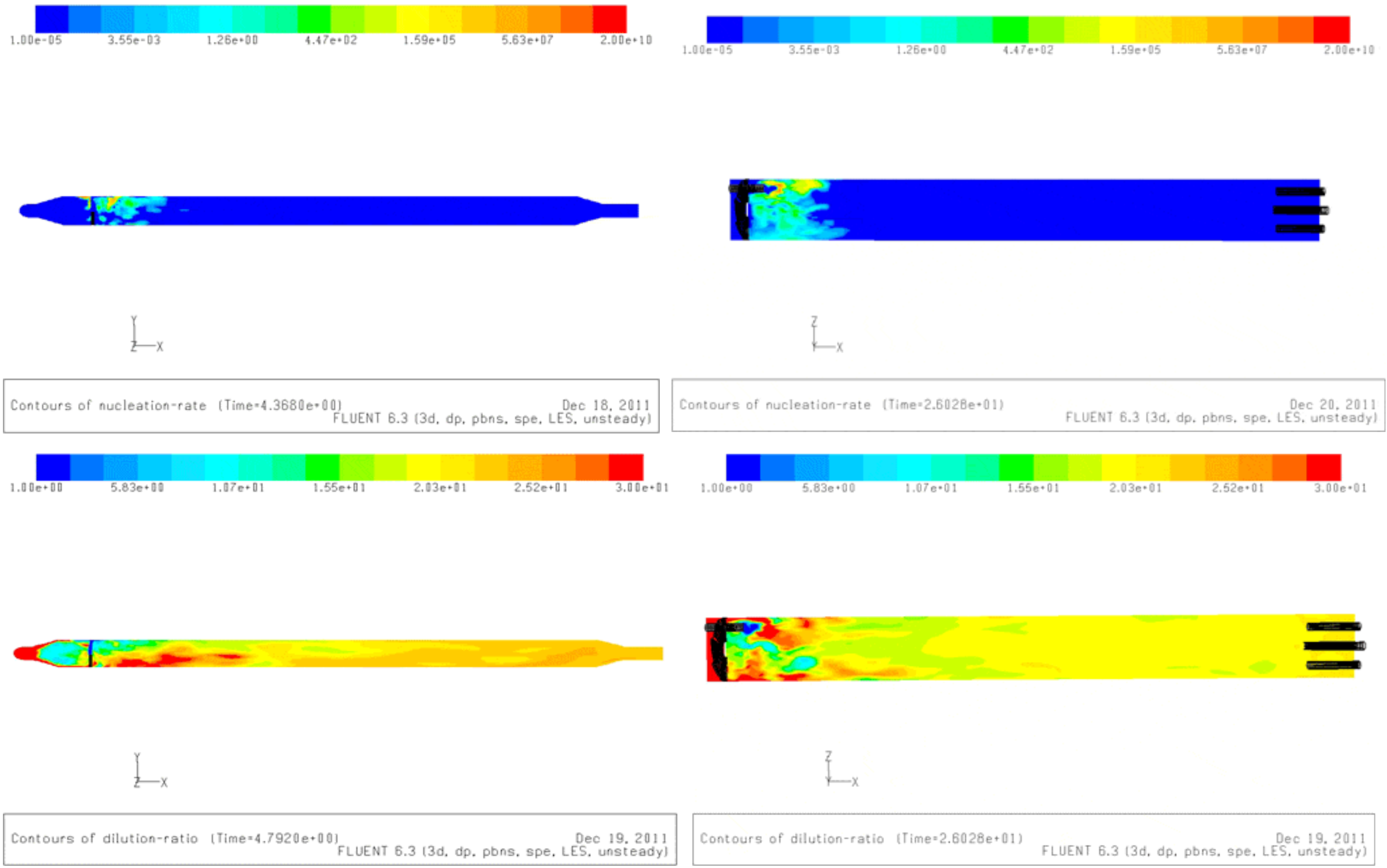
Wang et al. (2013) ES&T, 47:889-898

Predicted vs. Measured Particle Size Distributions





Wang et al. (2013) Environmental Science and Technology



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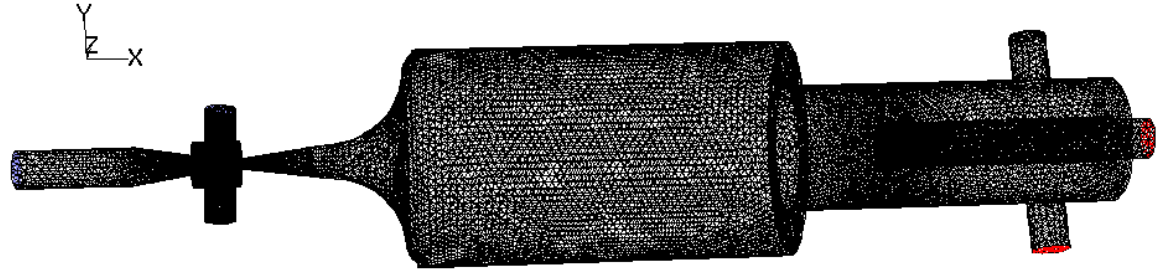
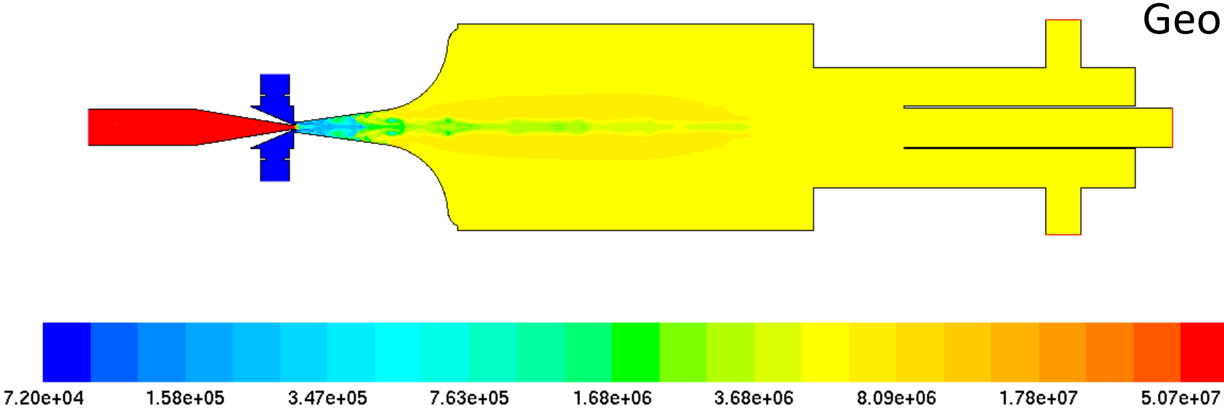
Ejector diluter

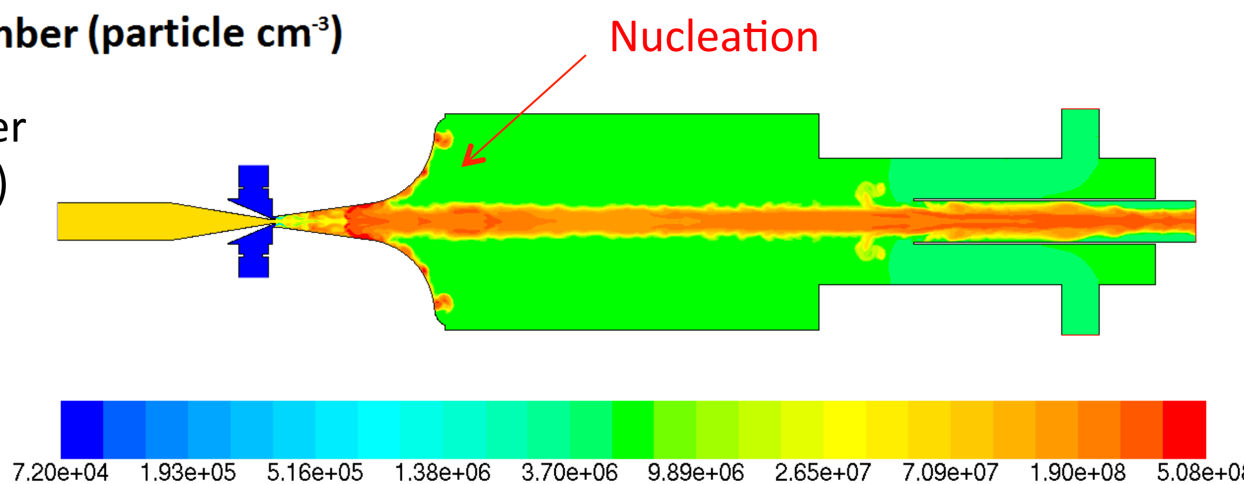


Geometry of the ejector diluter



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)

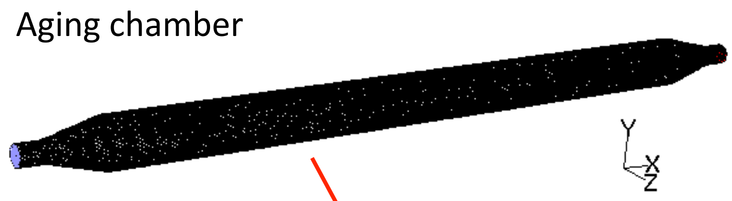
Manuscript in progress

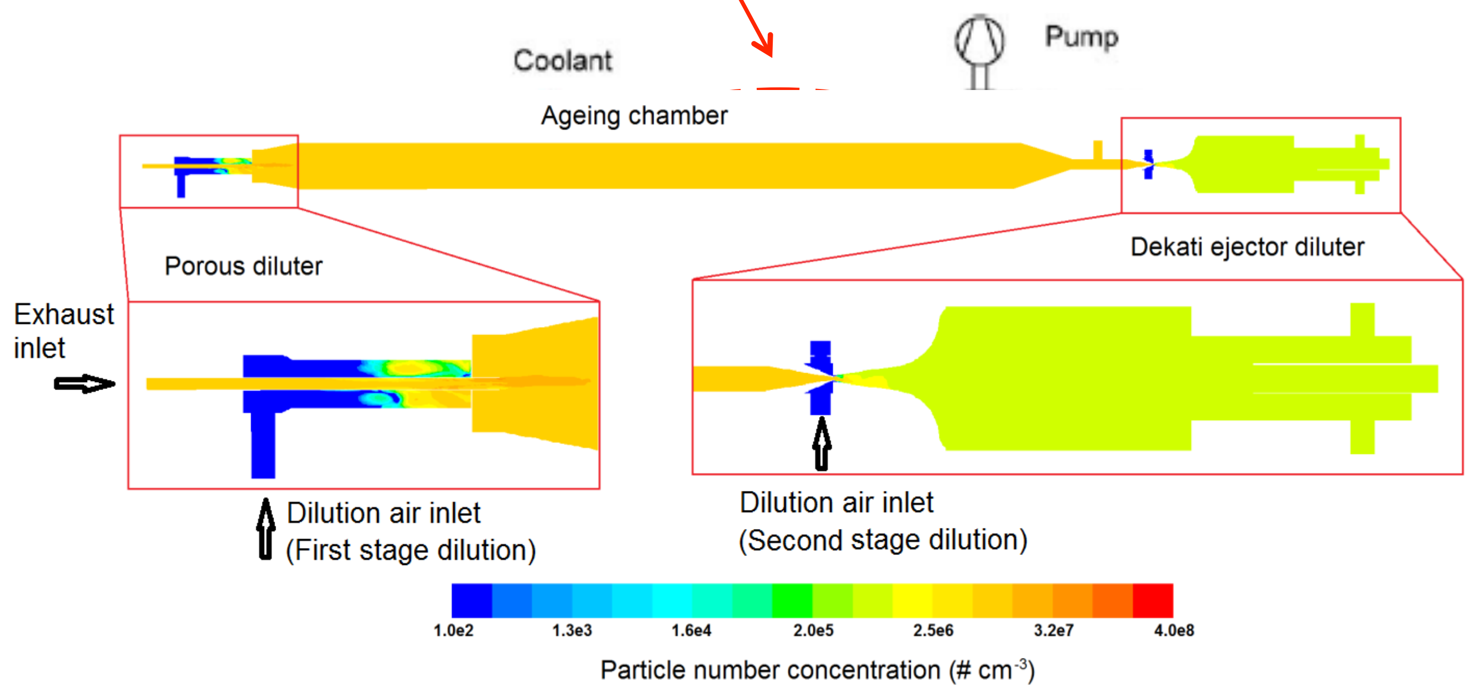
Rotating Disk Dilutor

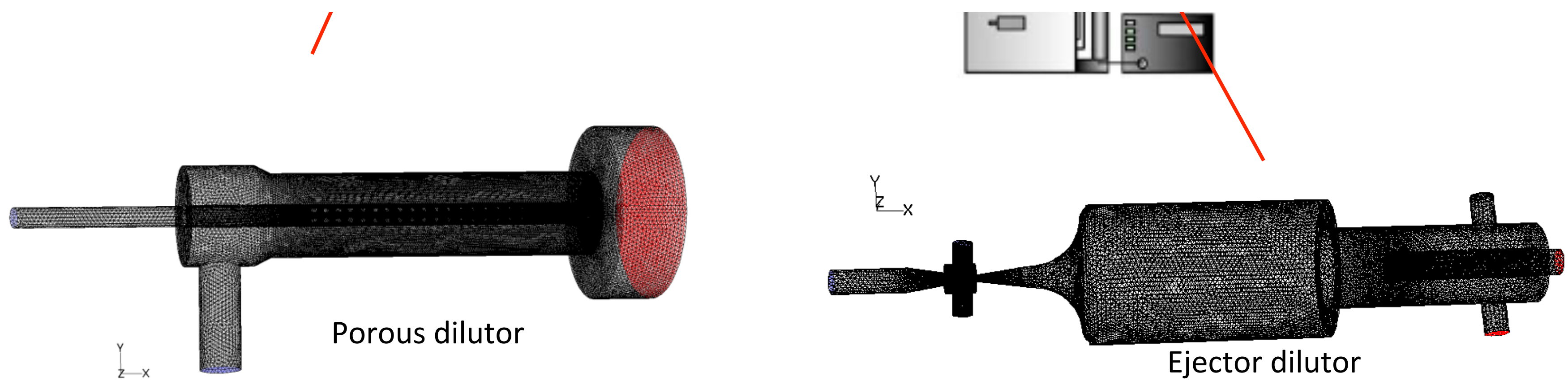
http://www.youtube.com/watch?v=-B1Nu2CUb14

Sampling train for the "Particulates" research program of EU

Manuscript in progress

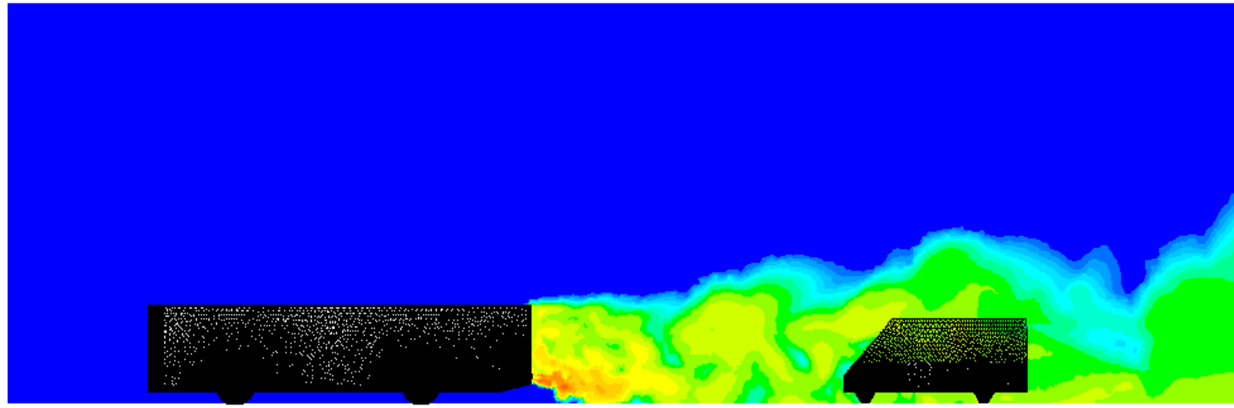






On-road Chasing

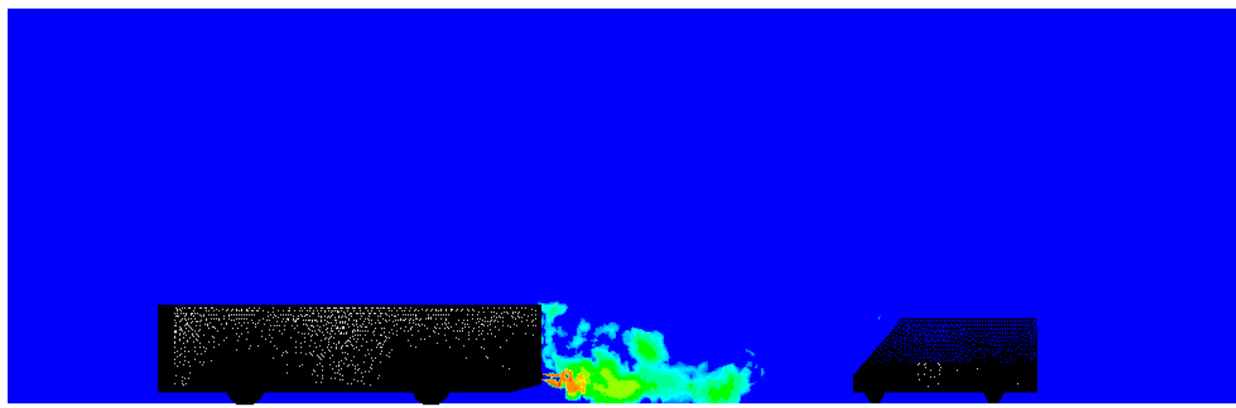
Wind inlet



(a) Heavy-duty diesel bus Chasing van

9.9e2 1.0e4 1.1e5 1.1e6 1.2e7 1.2e8 1.3e9

Particle number concentration (# cm^{-3})



(b)

1.0e-3 2.0e-1 3.8e1 7.5e3 1.5e6 2.9e8 5.6e10

Particle nucleation rate (# cm^{-3} s^{-1})

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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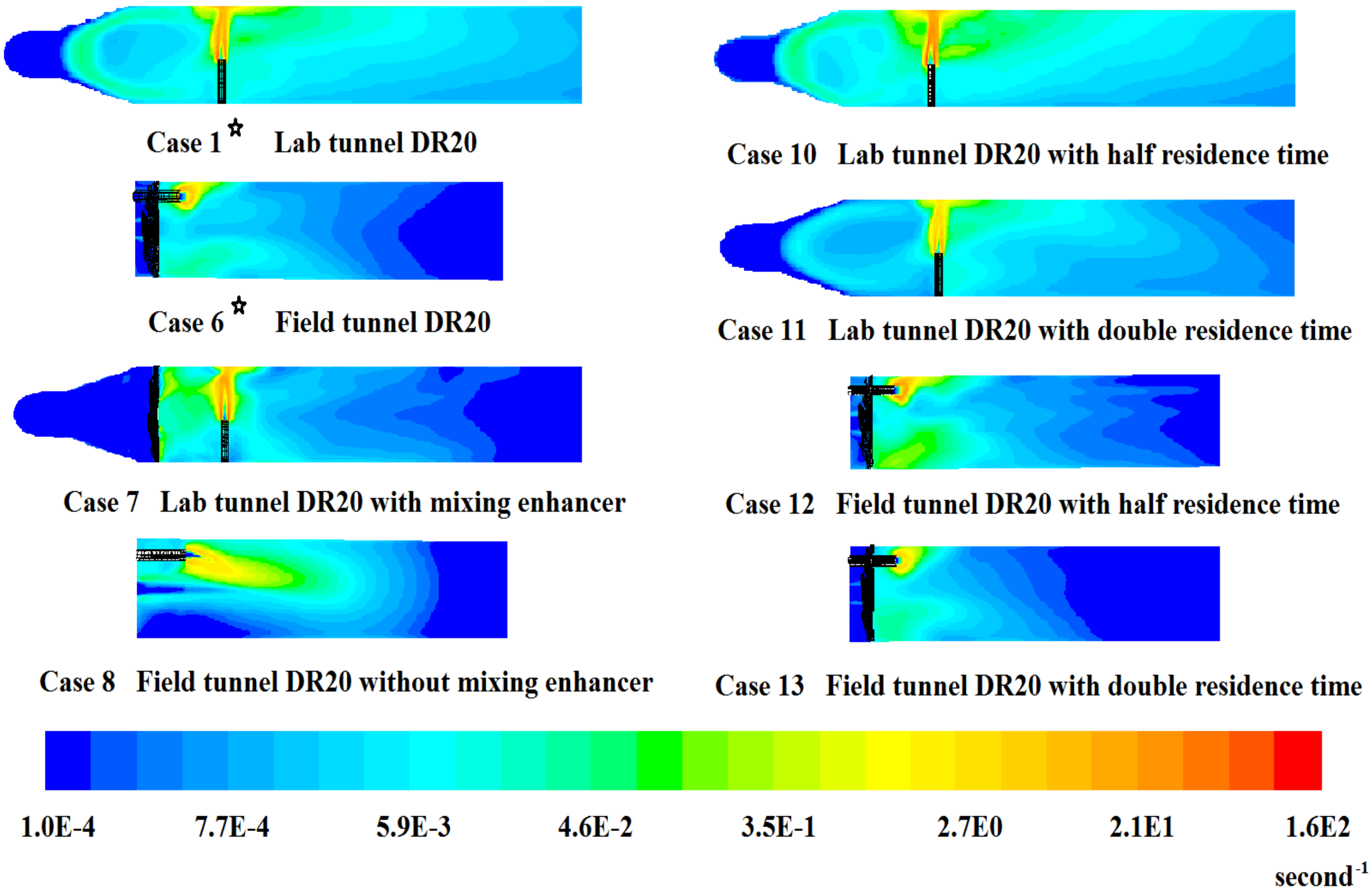
Time-averaged Dilution Rate



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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