Cornell University

Quantifying the Effects of the Turbulent Mixing Process in Fabricated Dilution Systems on Particulate Emission Measurements

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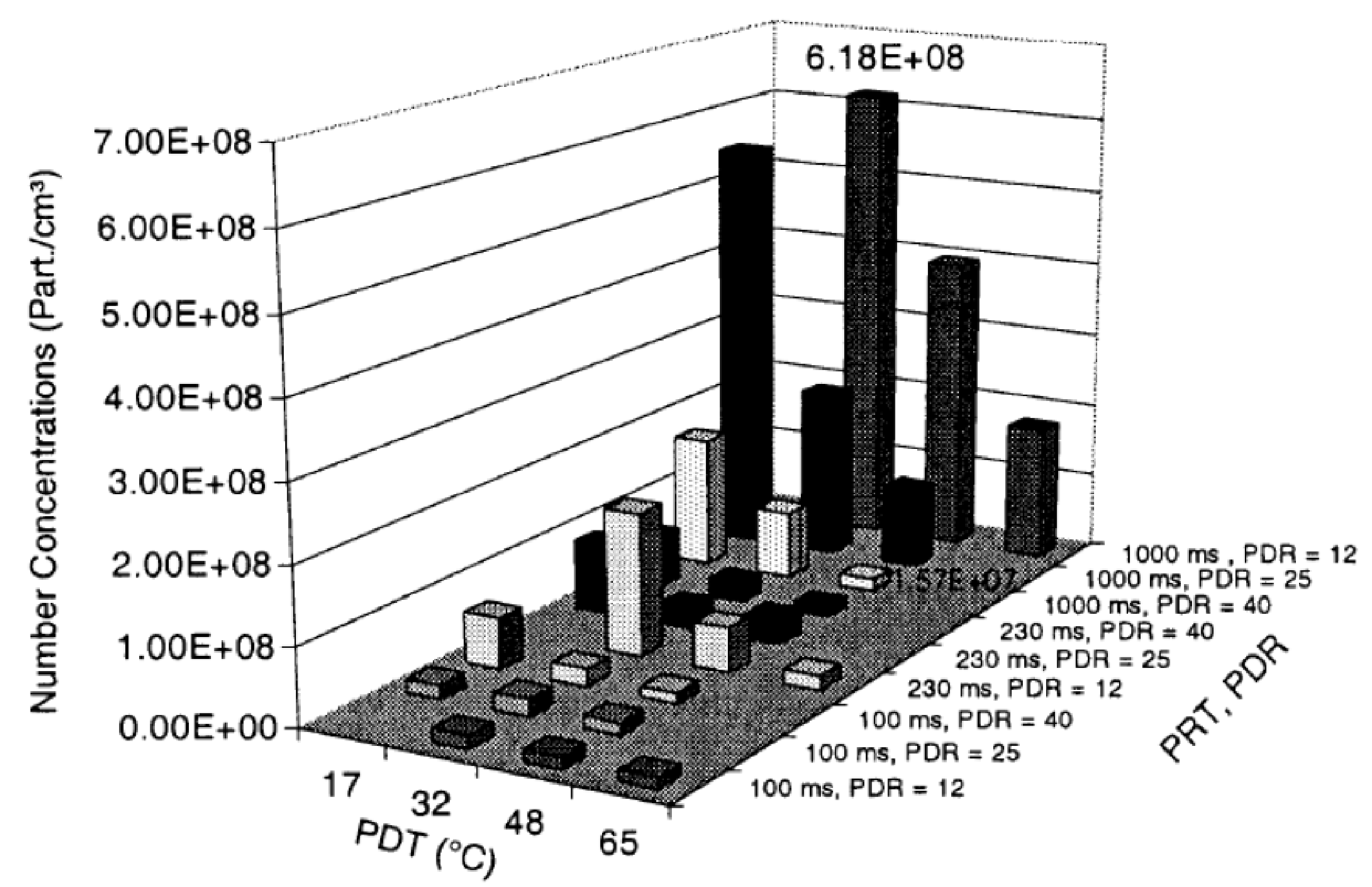
Dilution-based Emissions Measurements

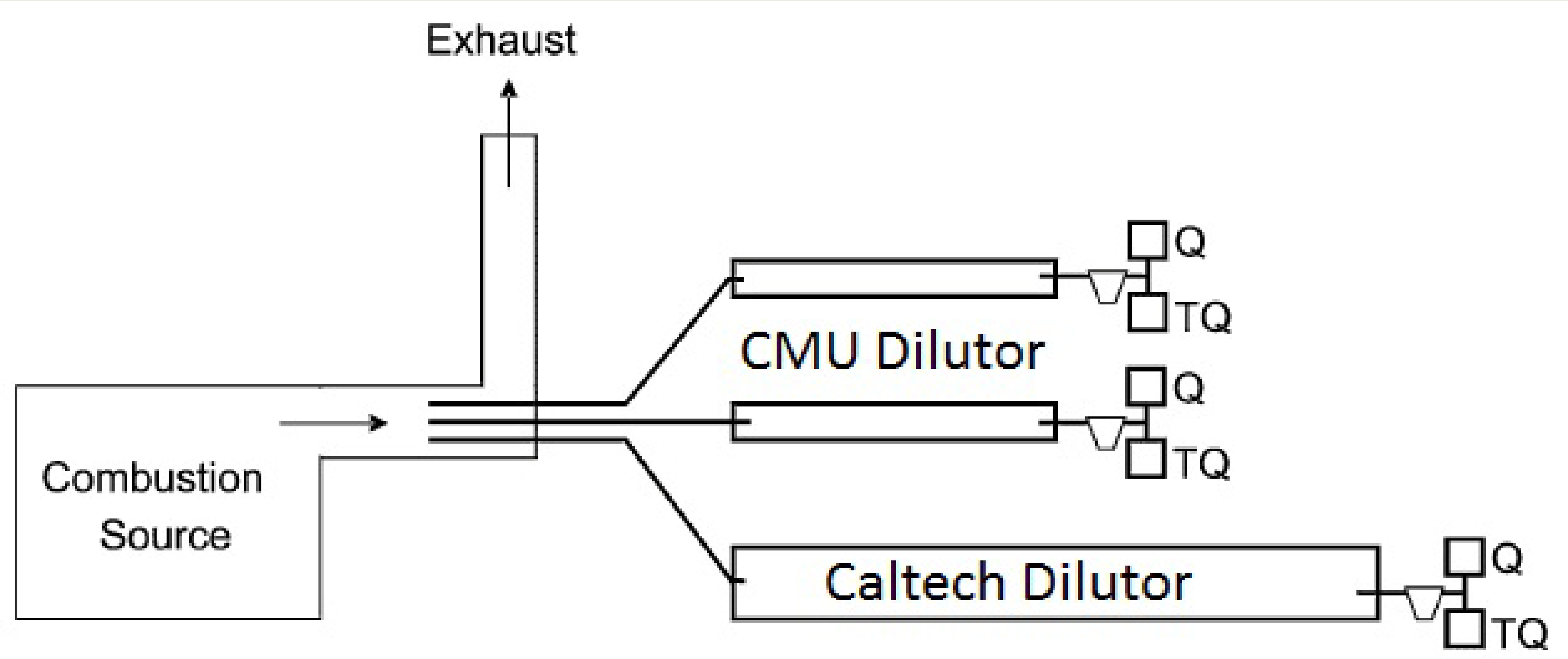
- The characterizations of combustion sources are almost entirely based on dilution-based emission measurements such (e.g., CVS dilution tunnels, PEMS).
- Why is the dilution necessary?
  - The temperature and the particle concentrations in the raw exhaust are typically too high to be analyzed directly.
  - Provide a controlled environment for emissions certification.
- Dilution-based emissions measurements have uncertainties.

Uncertainties

- Three major uncertainties:
  - Dilution parameters such as residence time, dilution temperature, and dilution ratio have a strong influence on particle size distributions and $PM_{2.5}$ mass.
  - The measurement results from different dilution tunnels are not directly comparable as they are sensitive to dilution conditions.
  - Laboratory emission measurements may differ considerably from on-road emissions depending on chosen dilution parameters.



Dilution parameters such as residence time, dilution temperature, and dilution ratio have a strong influence on number concentrations.



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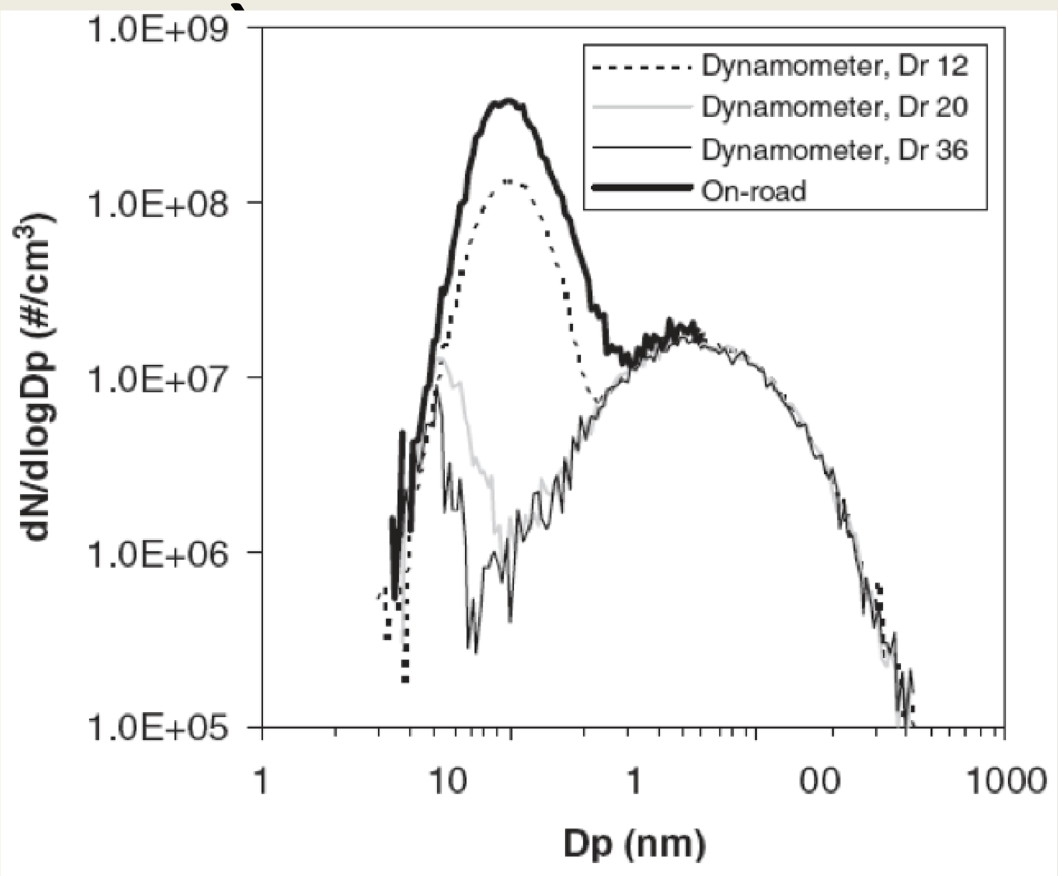

Laboratory emission measurements may differ considerably from on-road emissions depending on chosen dilution parameters.

Proposed Work

- **Hypothesis**: The differences in the mixing processes in the corresponding emission measurement environments are a major contributor to the observed discrepancies.
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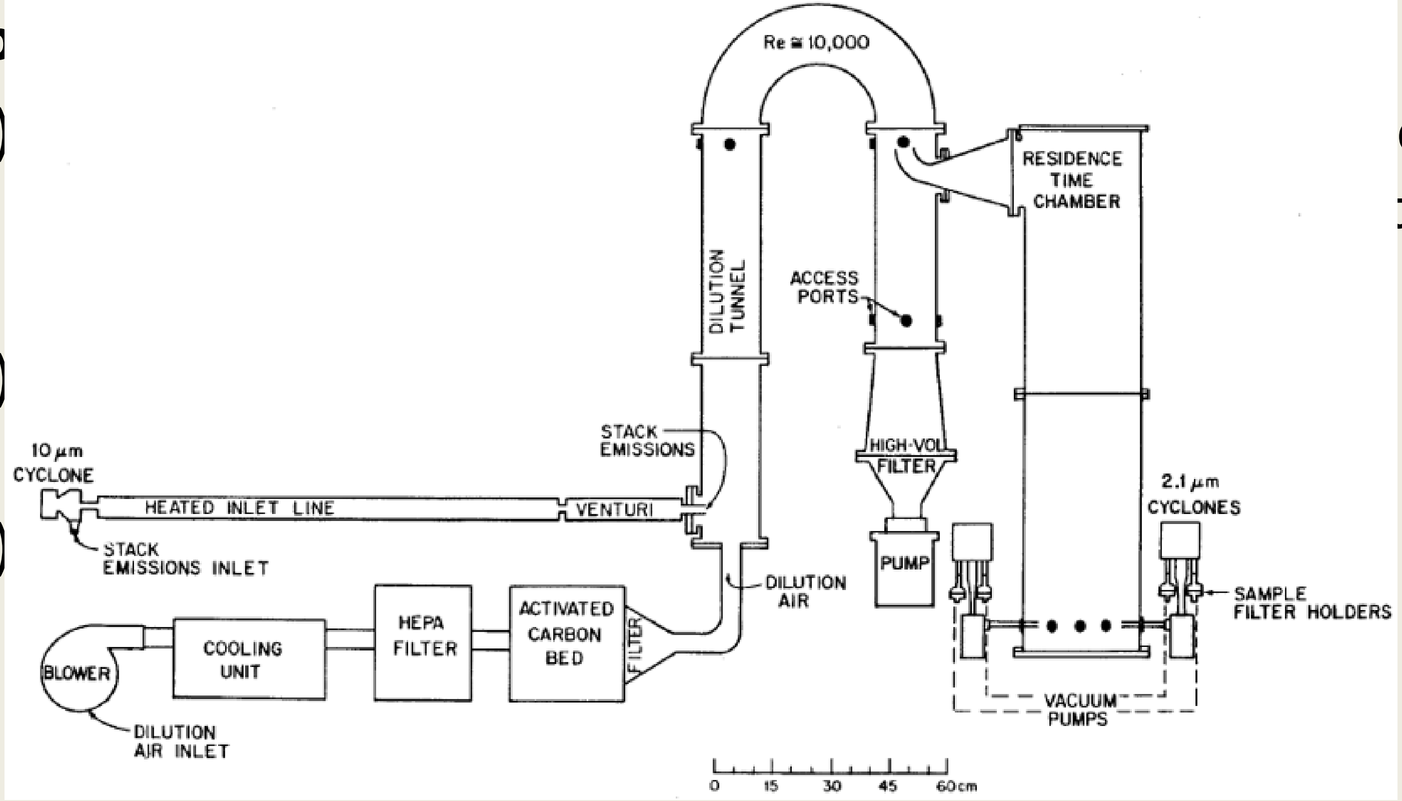
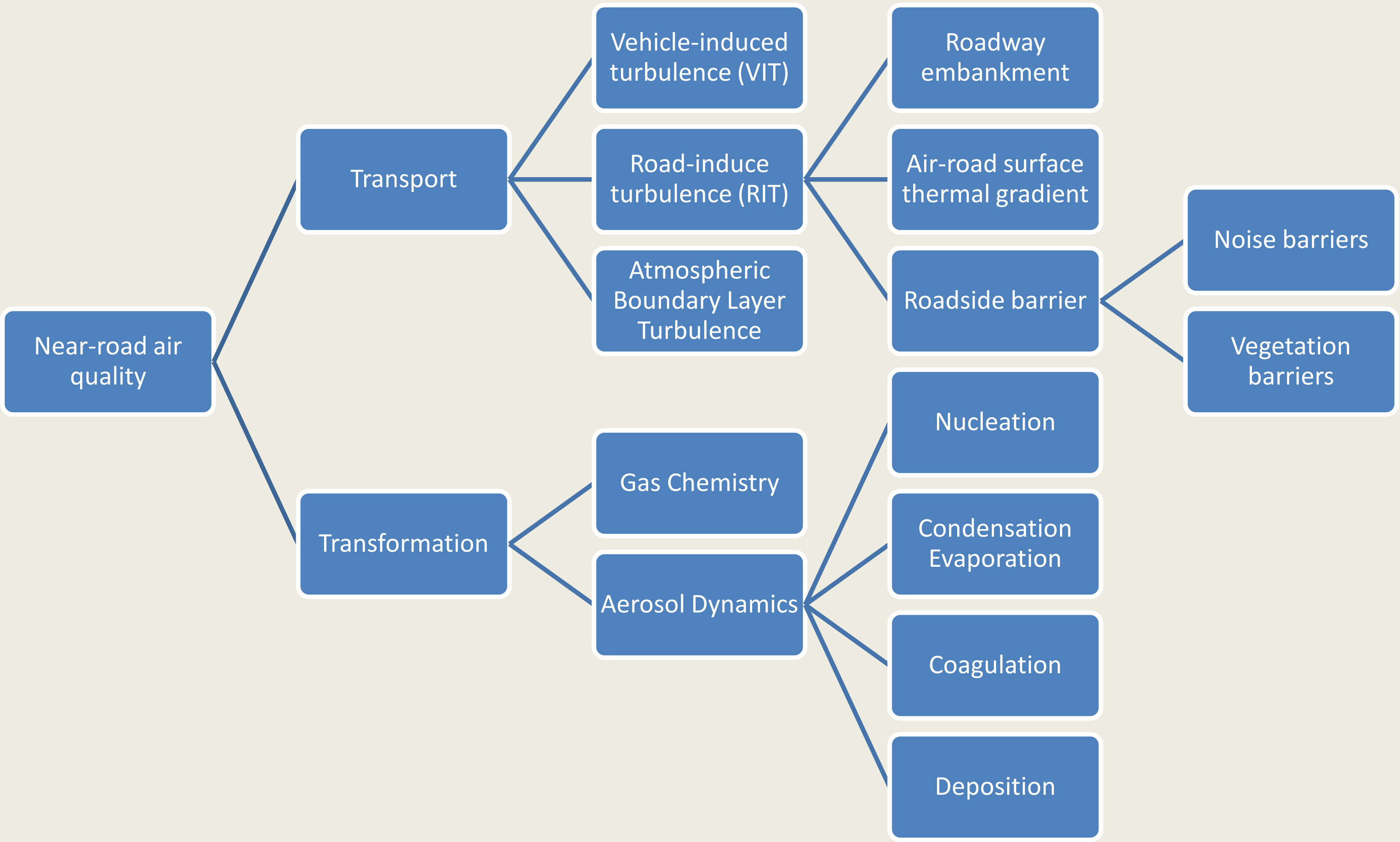


Approach

- **Guiding principle**: The evolutions of exhaust properties taking place inside the emission measurement systems and in the atmosphere are governed by the same physics and chemistry, i.e., they are both ***turbulent reacting flows.***
- Tool: an advanced turbulent reacting flow model, **CTAG** (**C**ornell **T**urbulent **A**erosol dynamics and **G**as chemistry model)
- CTAG couples the Computational Fluid Dynamics (CFD) model with Aerosol Dynamics and Gas Chemistry modules

CTAG Framework

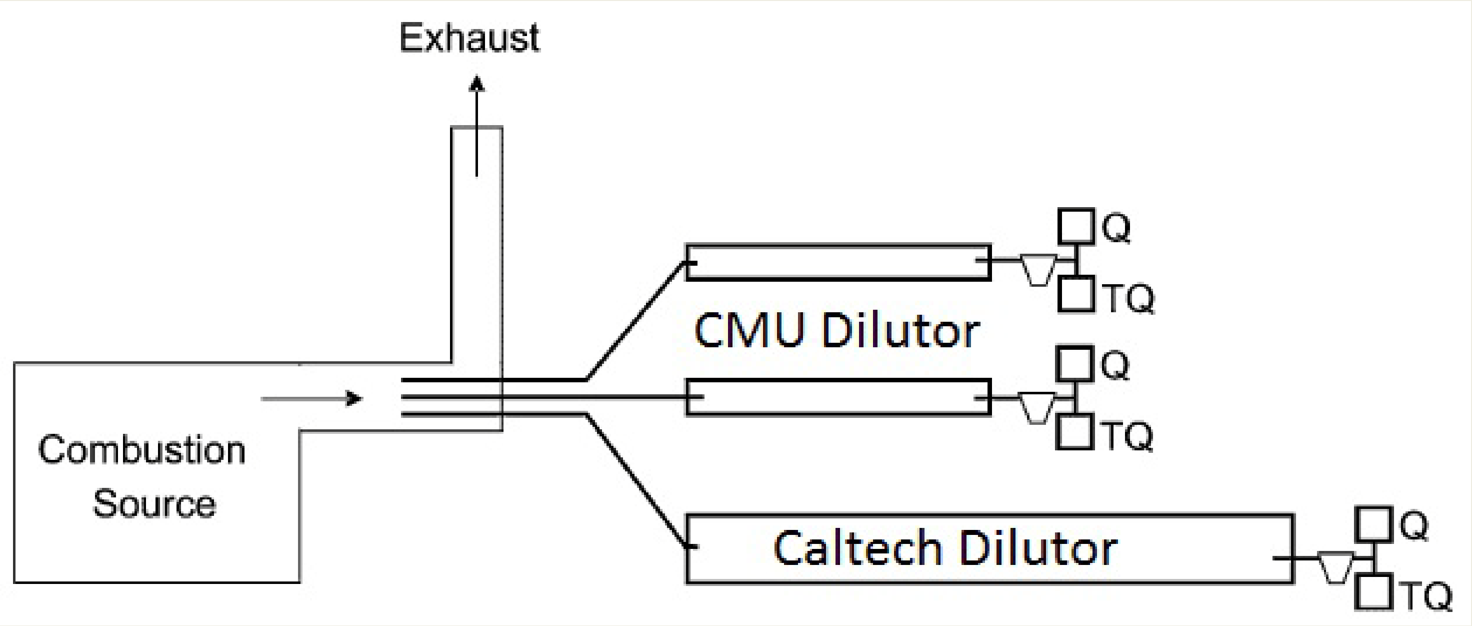


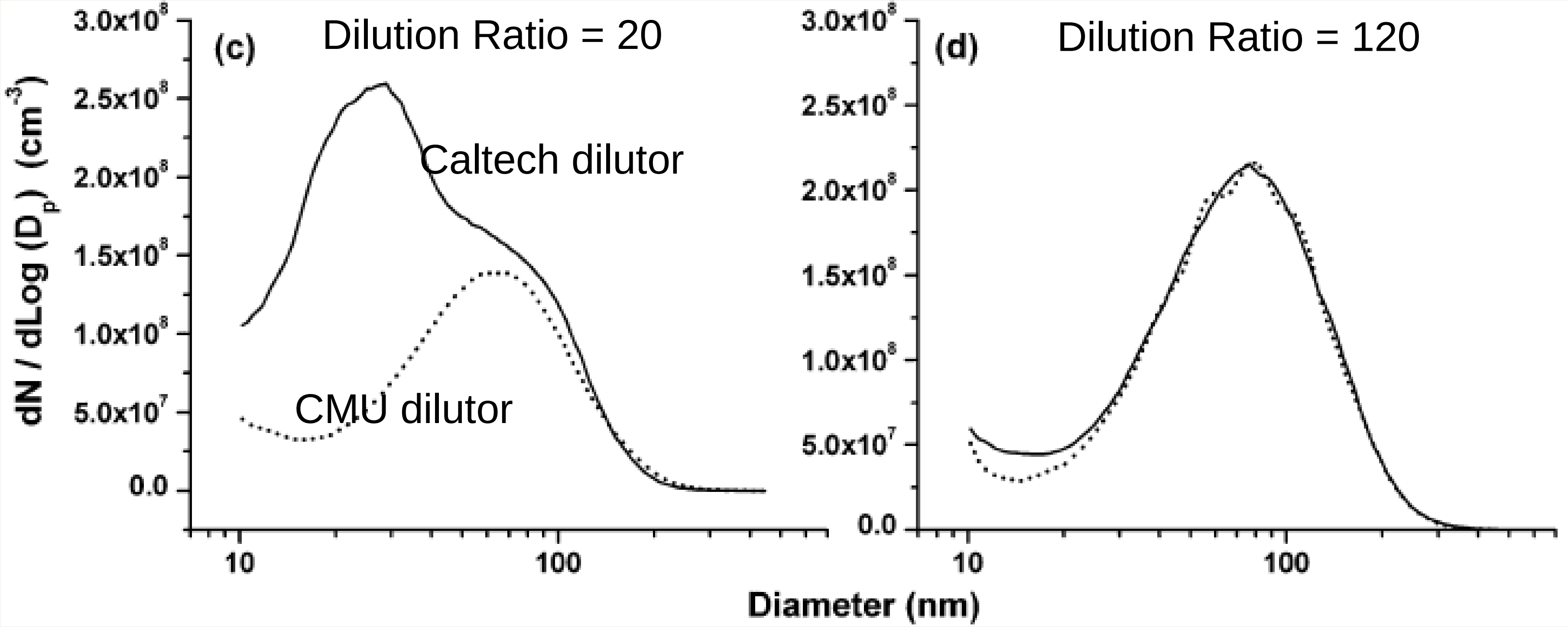
Experimental Data

- Comparison between different dilution tunnels (Lipsky and Robinson, 2005)
- Comparison between full-scale wind tunnel measurement and CVS dilution tunnel measurement of heavy duty diesel exhaust (ongoing, supported by CARB)
- Comparison between on-road measurement and dilution tunnel measurement of vehicle exhaust (Ronkko et al., 2006)*

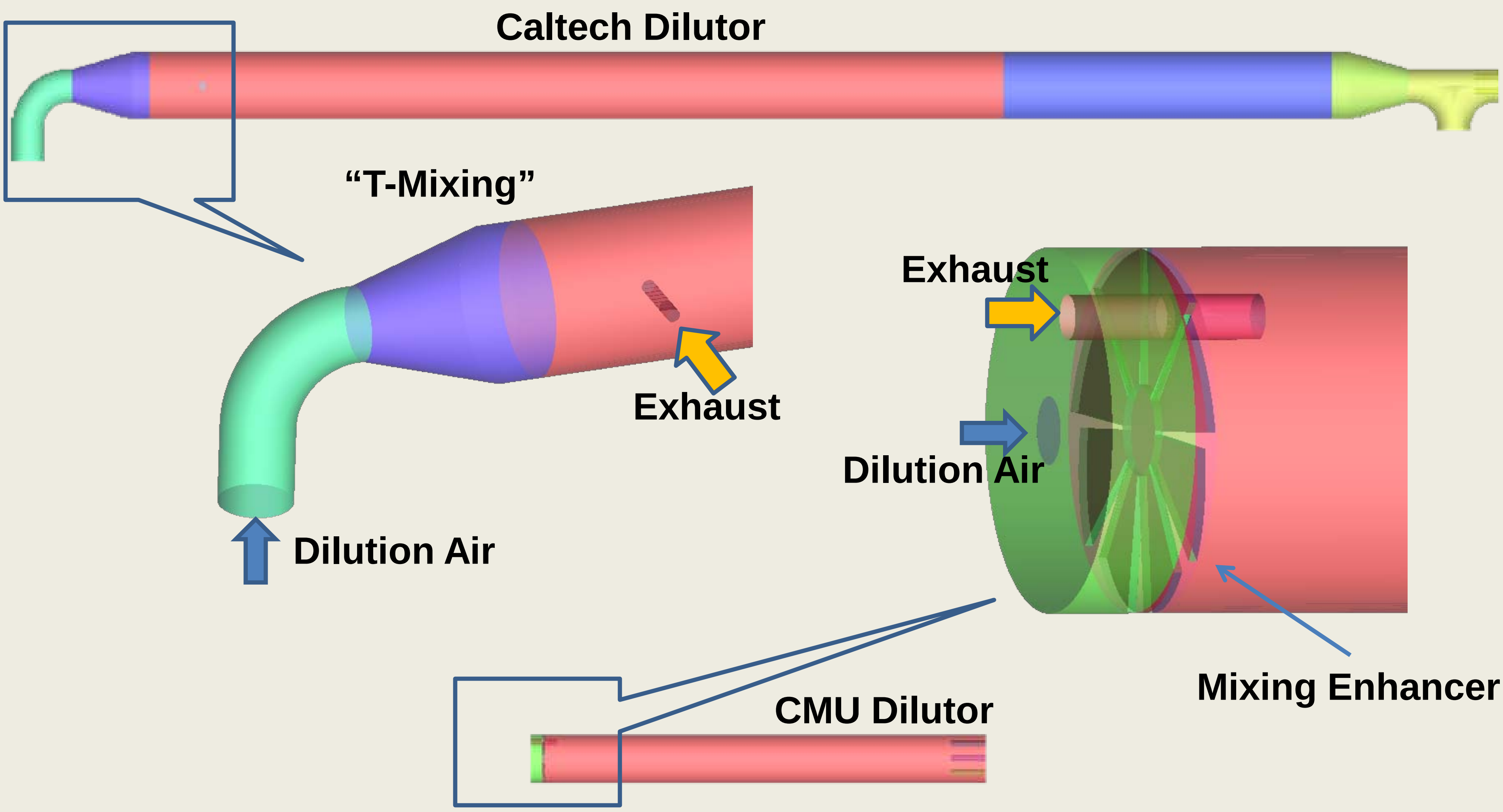
*: Exploratory, not in the original proposal

Some preliminary results


Exhaust
Combustion
Source
CMU Dilutor
Caltech Dilutor
Q
TQ


(c)
Dilution Ratio = 20
Caltech dilutor
CMU dilutor
(d)
Dilution Ratio = 120
dN / dLog (D$_p$) (cm^{-3})
3.0x10^8
2.5x10^8
2.0x10^8
1.5x10^8
1.0x10^8
5.0x10^7
0.0
10
100
Diameter (nm)

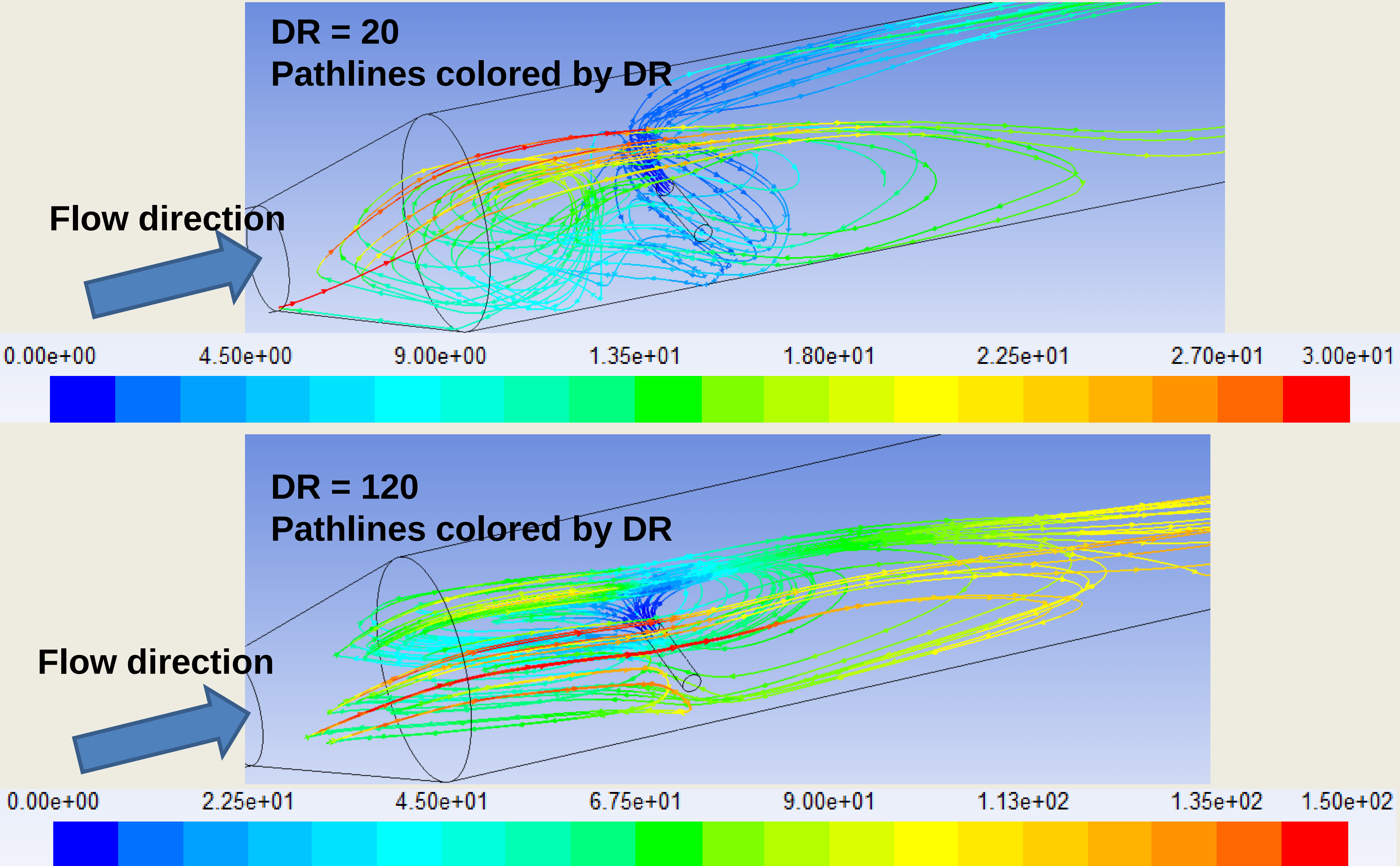
Dilutors Geometry



Different Dilution Ratio Settings

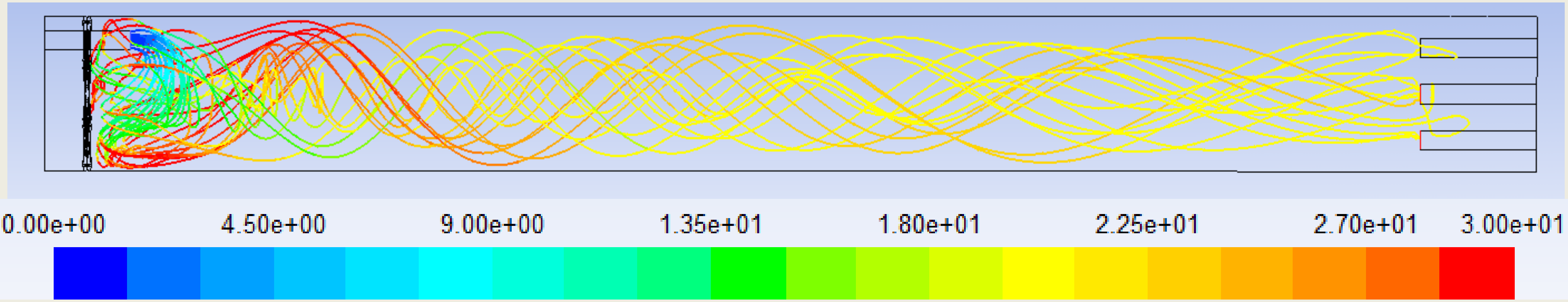
- Calculate the Dilution Ratio (DR) by CO_2 mole fraction
- Keep the dilution air flow rate as a constant
- Realize the Dilution Ratio by adjusting the flow rate of the exhaust
- Two DR were considered, DR=20 and DR=120, because of the experimental data.

Caltech Dilutor: Pathlines at different DR

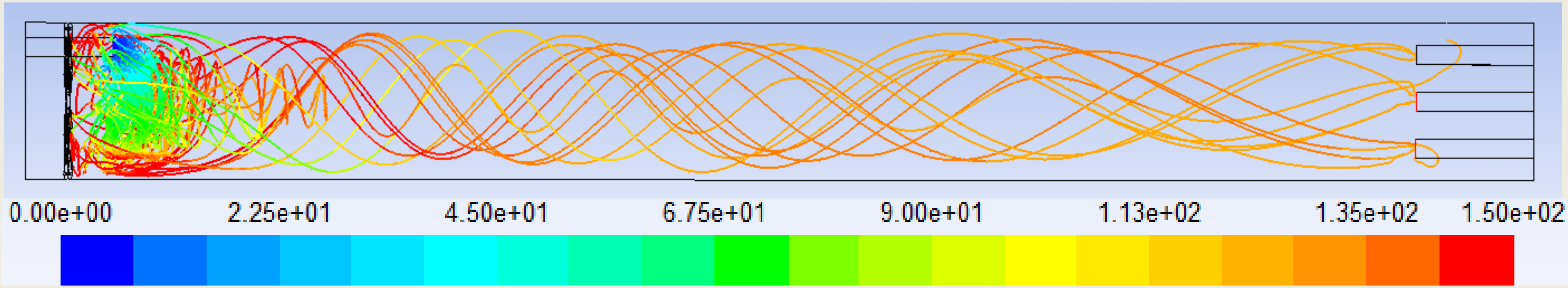


CMU Dilutor: Pathlines at different DR

DR = 20 Pathlines colored by DR

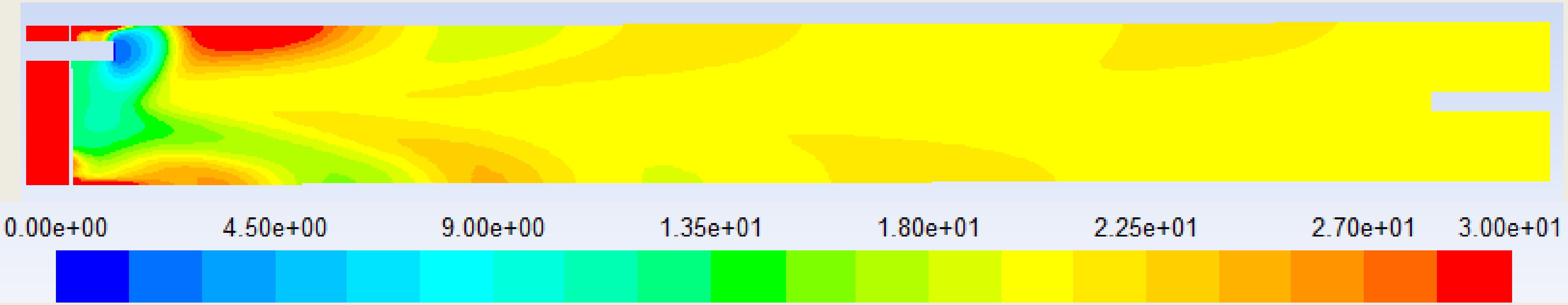


DR = 120 Pathlines colored by DR

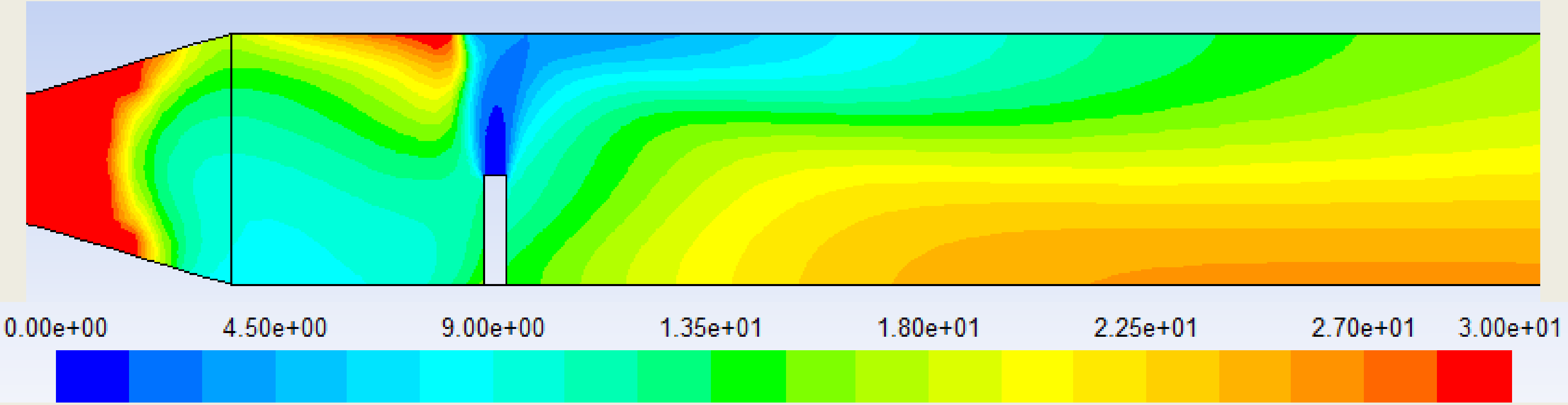


Comparison: Dilution Ratio Distribution at DR=20

CMU Dilutor Dilution Ratio Distribution

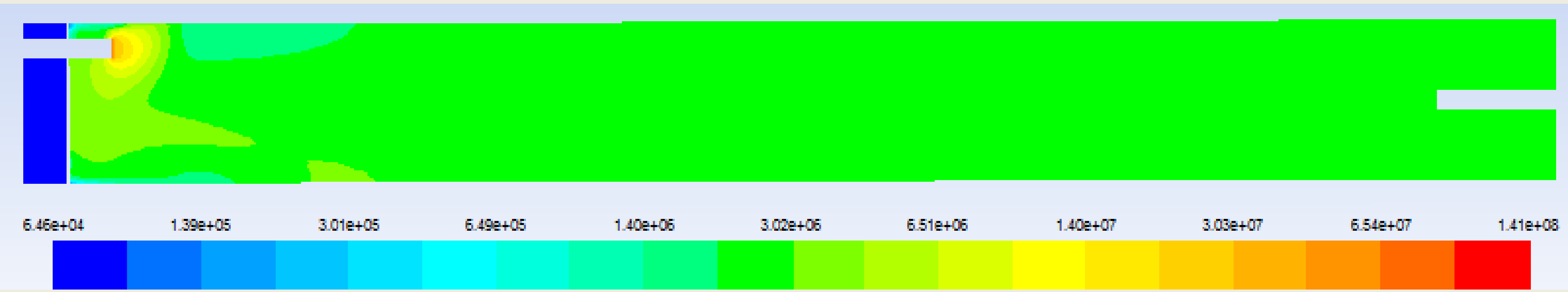


Caltech Dilutor Dilution Ratio Distribution

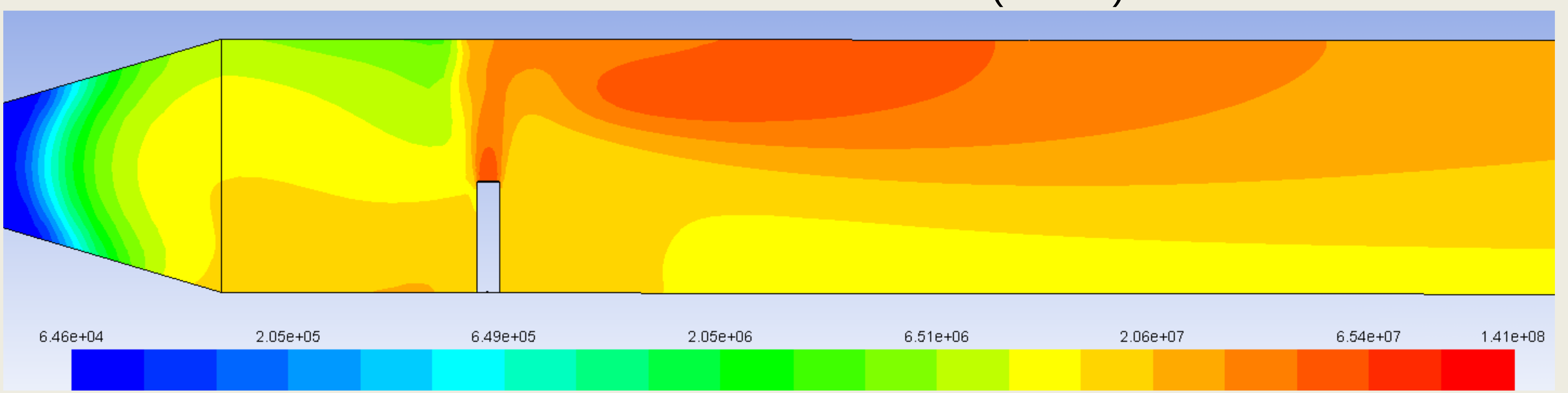


Comparison: Total number concentration at DR=20

CMU Dilutor Total Number Concentration (#/cm^{-3})

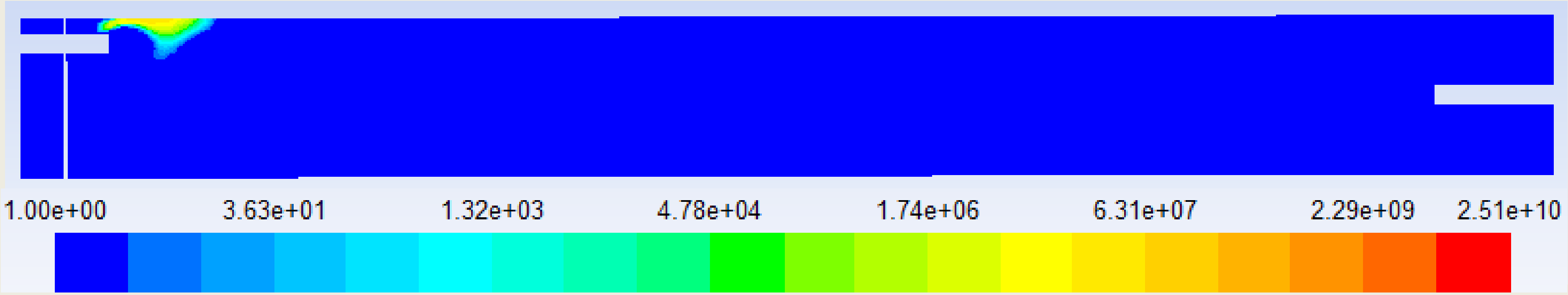


Modified Caltech Dilutor Total Number Concentration (#/cm^{-3})

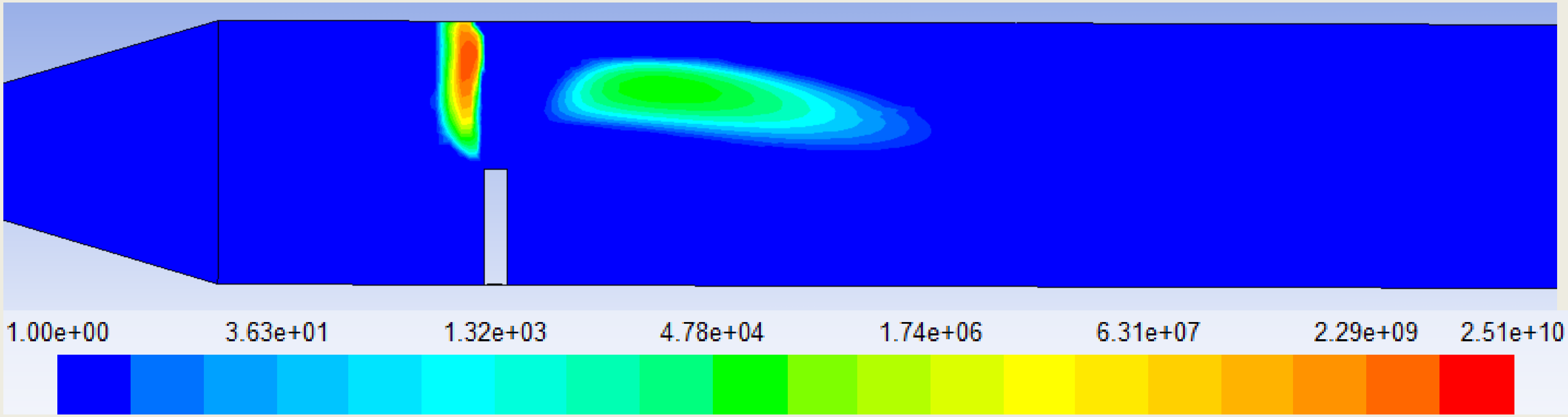


Comparison: Nucleation rates at DR=20

CMU Dilutor Nucleation Rate ($\#/cm^{-3}s^{-1}$)

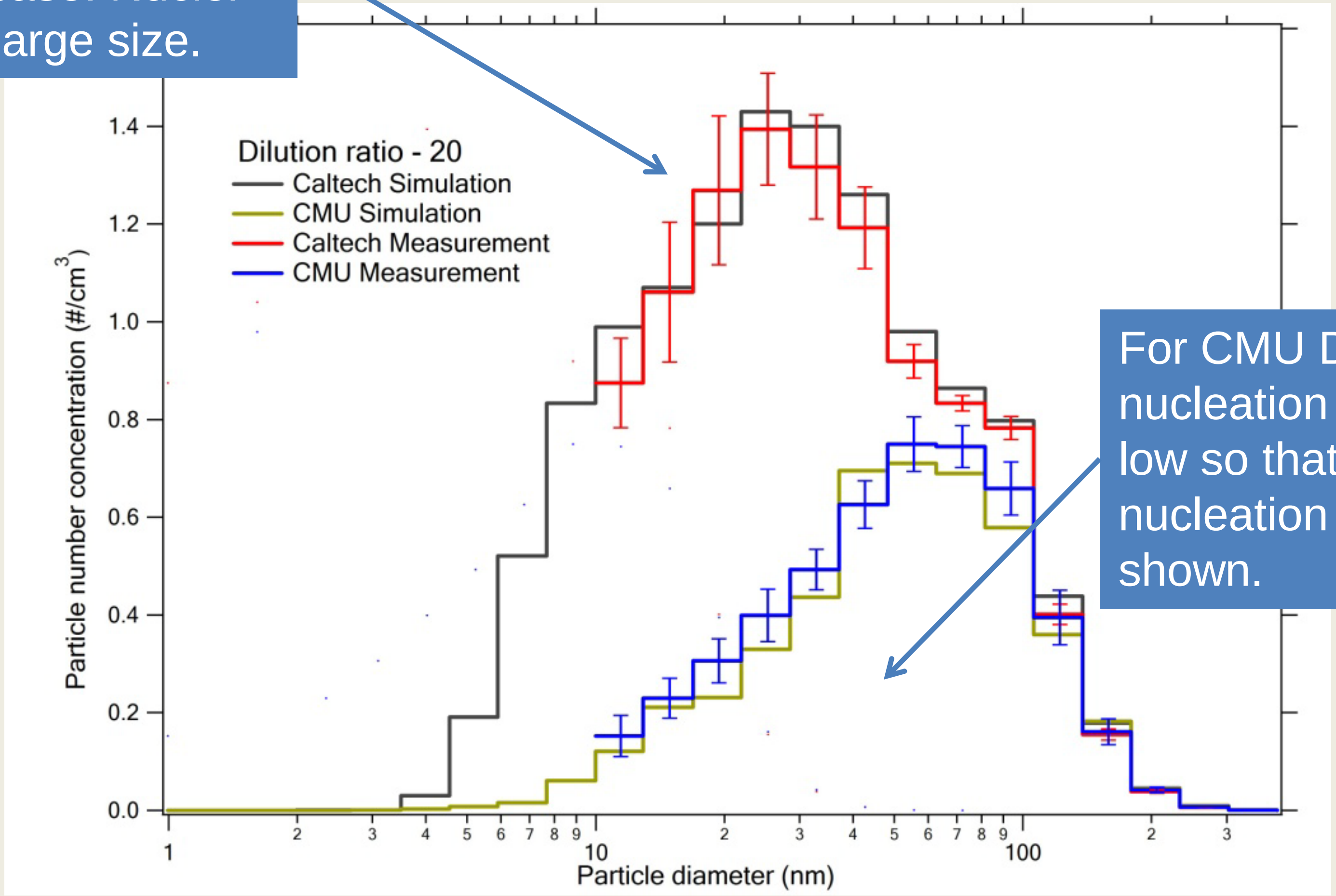


Caltech Dilutor Nucleation Rate ($\#/cm^{-3}s^{-1}$)



Simulation Results: DR=20

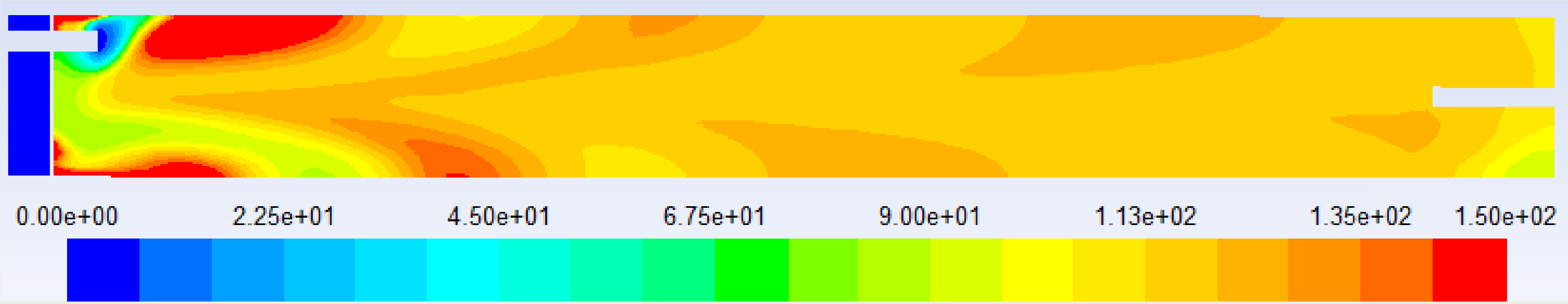
For Caltech dilutor, nucleation rate is high at DR 20 case. Nuclei grow into large size.



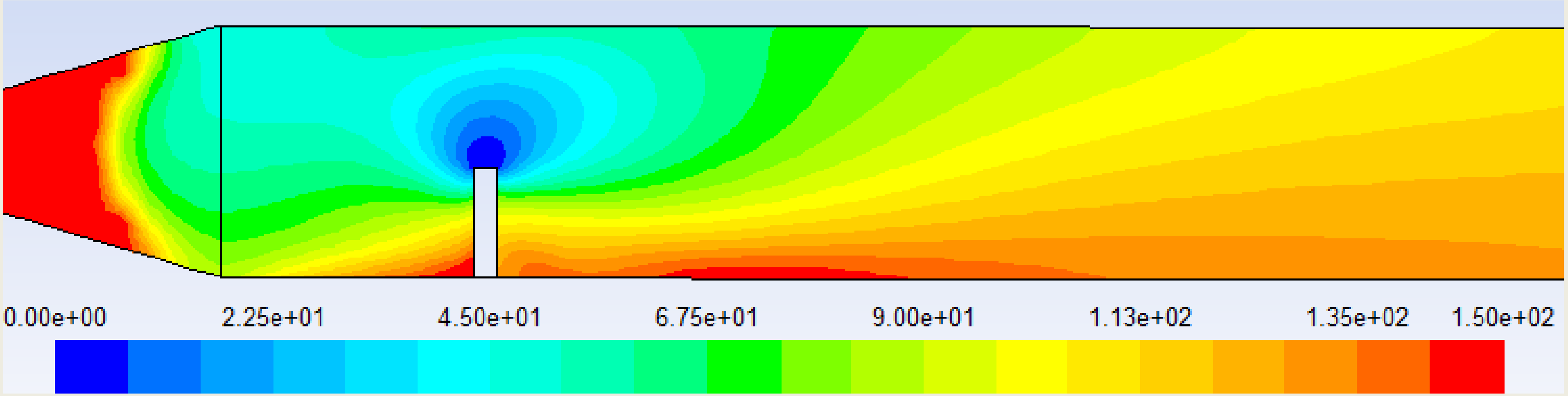
For CMU Dilutor, the nucleation rate is very low so that virtually no nucleation mode is shown.

Comparison: Dilution Ratio Distribution at DR=120

CMU Dilutor Dilution Ratio Distribution

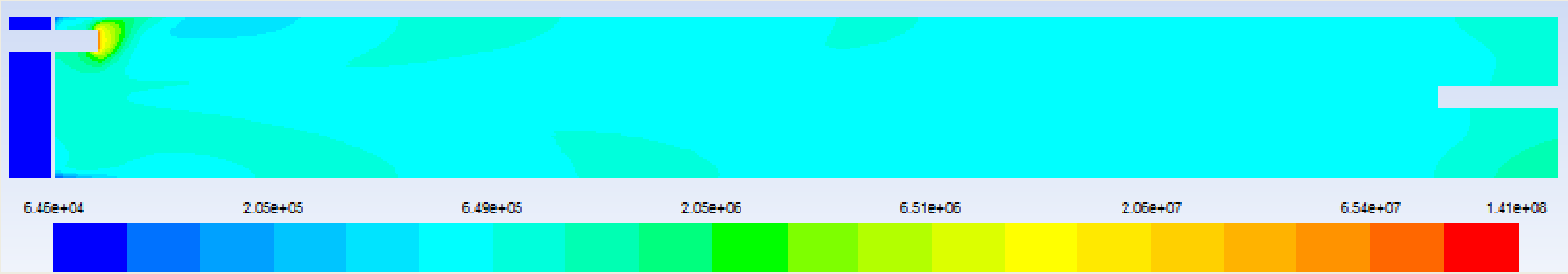


Caltech Dilutor Dilution Ratio Distribution

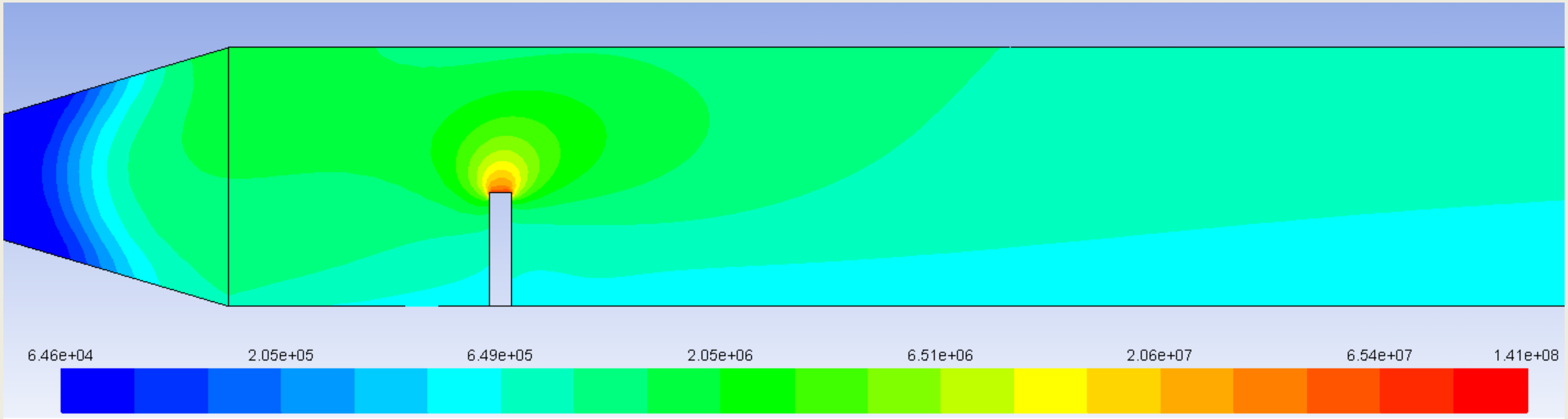


Comparison: Total number concentration at DR=120

CMU Dilutor Total Number Concentration (#/cm^{-3})

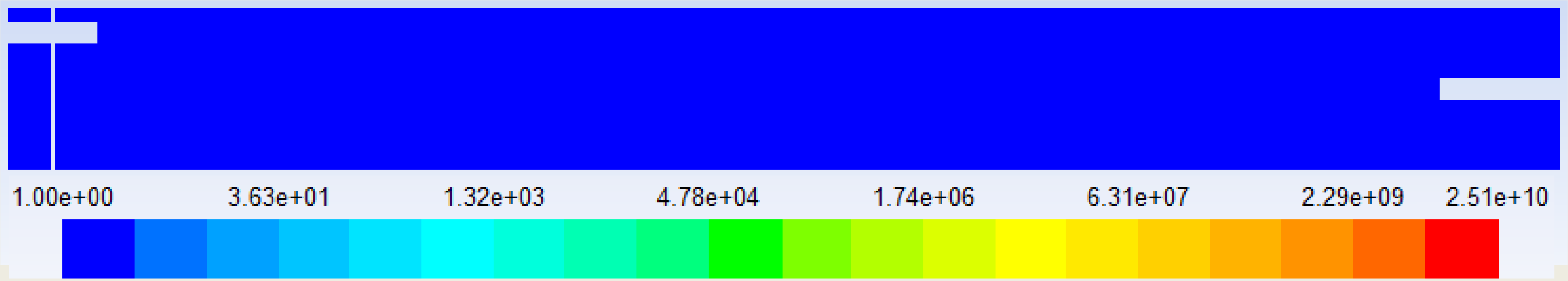


Modified Caltech Dilutor Total Number Concentration (#/cm^{-3})

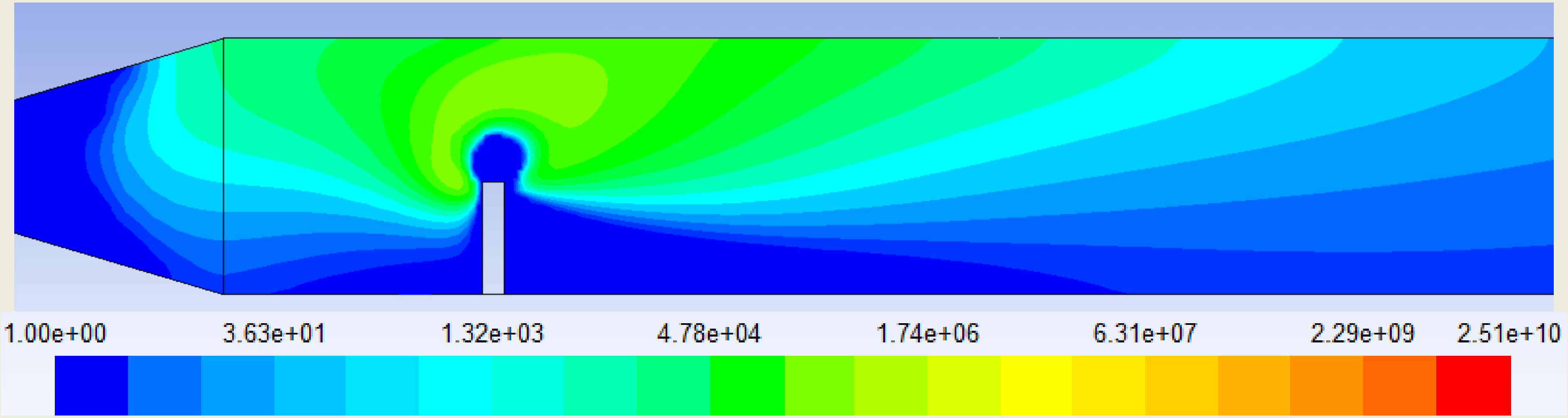


Comparison: Nucleation rates at DR=120

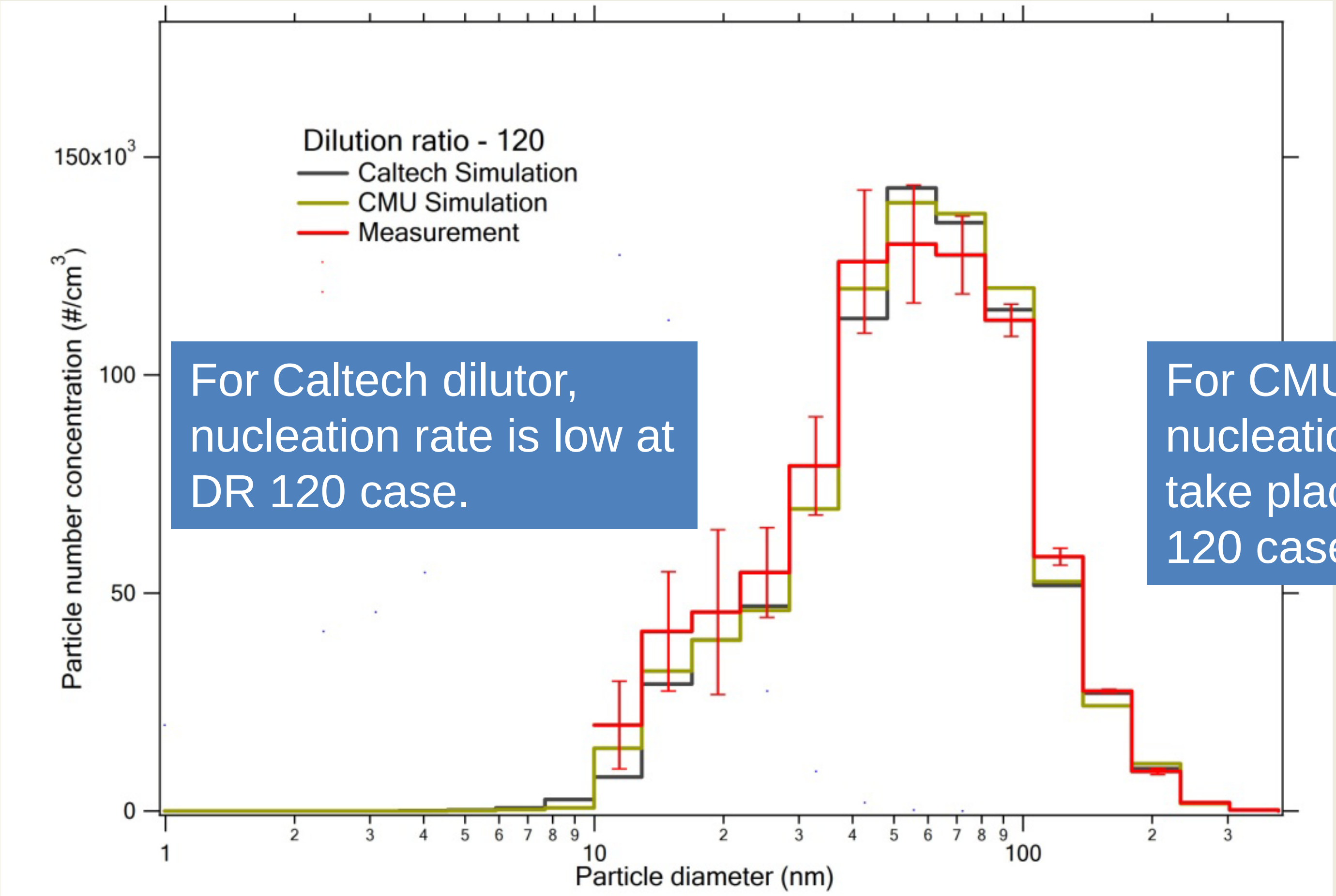
CMU Dilutor Nucleation Rate (#/cm^{-3}s^{-1})



Modified Caltech Dilutor Nucleation Rate (#/cm^{-3}s^{-1})



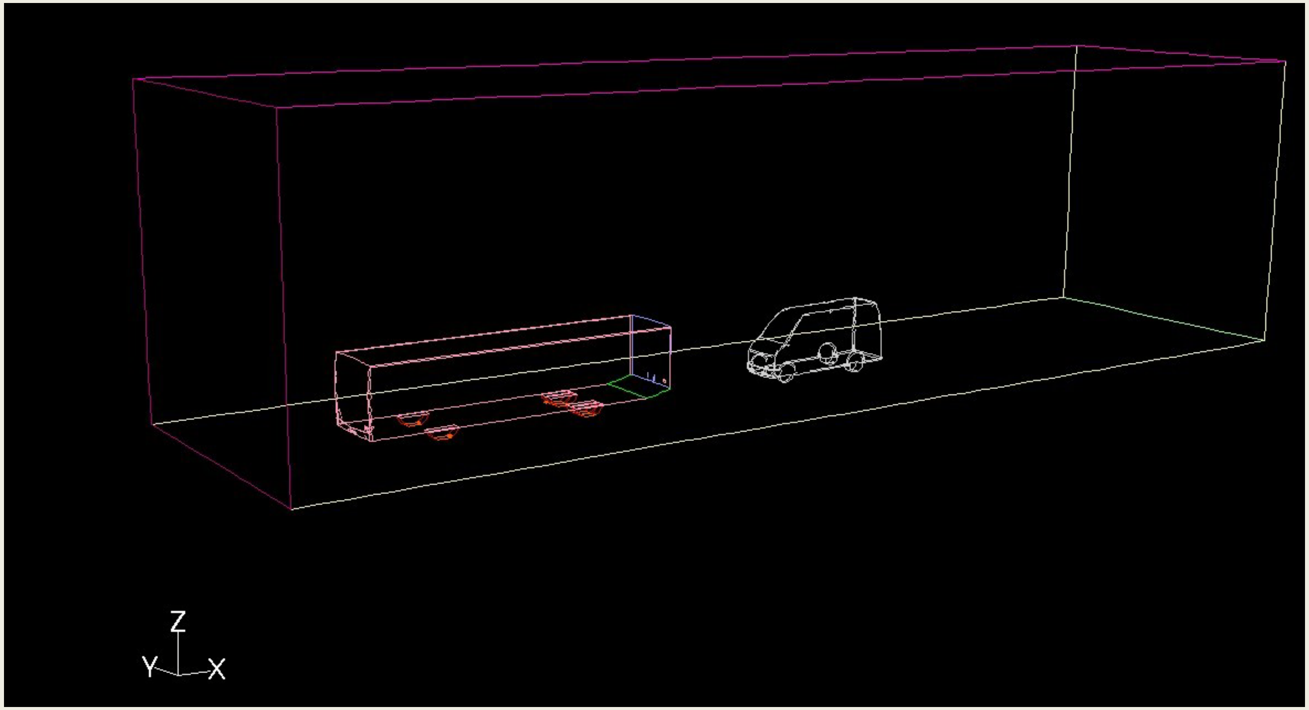
Simulation Results: DR=120

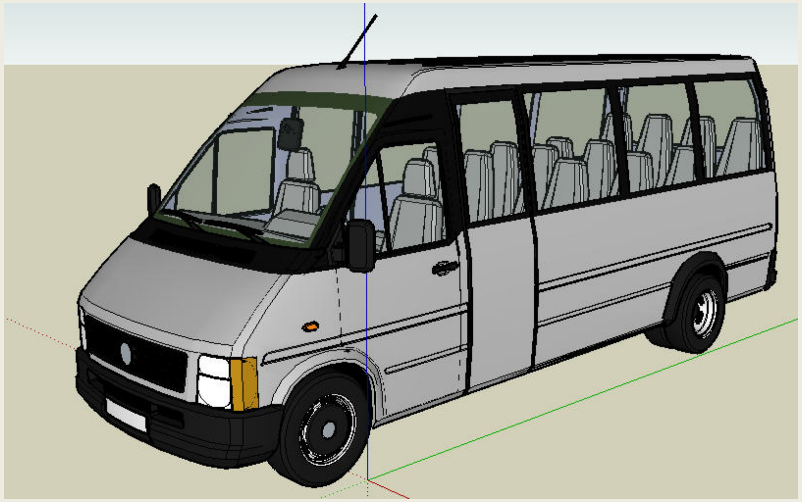


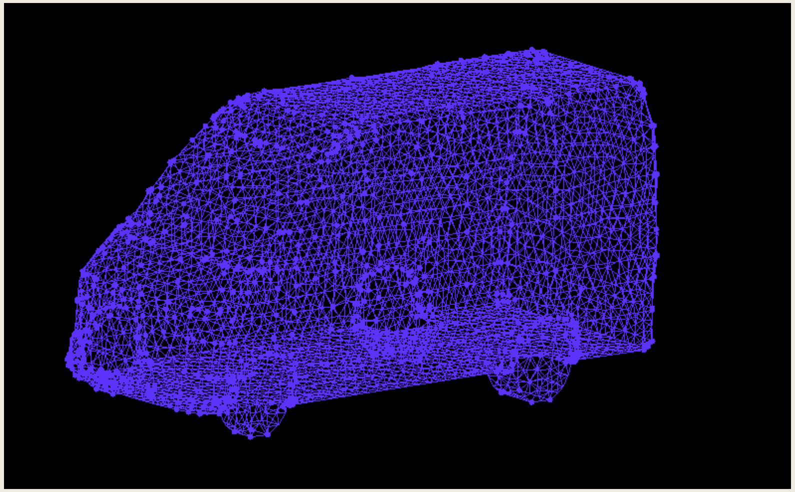
For Caltech dilutor, nucleation rate is low at DR 120 case.

For CMU Dilutor, nucleation did not take place at DR 120 case.

No nucleation mode is observed for DR 120 case, mainly due to the high dilution ratio.


Z
Y
X





Summary

- Combining controlled experiments and advanced turbulent reacting flow models enables us to achieve a mechanistic understanding of the effects of dilution conditions on PM measurement.
- We are able to explain quantitatively the discrepancies between the measurement results from the two types of dilution tunnels.
- The question to be answer is what is the design objective of the dilution systems.

Acknowledgement

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