Novel dilution sampling method for combustion emissions

Jorma Jokiniemi

Fine Particle and Aerosol Technology Laboratory, University of Eastern Finland, P.O Box 1627, FI-70211, Kuopio, Finland

UNIVERSITY OF EASTERN FINLAND

1st INTERNATIONAL REAL-LIFE EMISSIONS WORKSHOP ON SMALL-SCALE COMBUSTION 8.-10.11.2022: The measurement methods, and emission components for the solid fuel combustion appliances

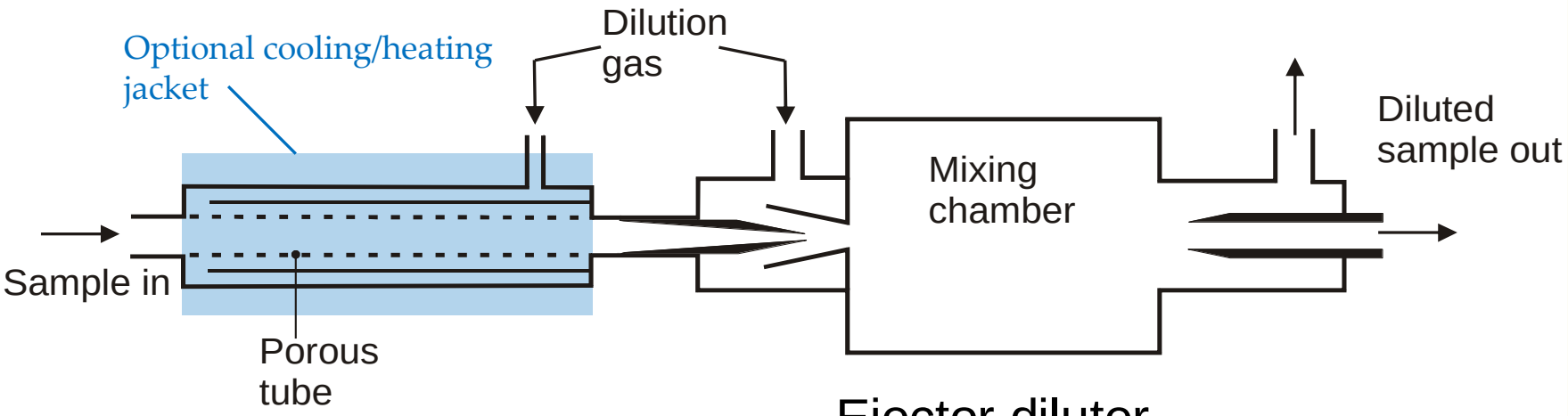
Contents

1. Background:
   Porous tube - ejector dilution systems
2. Measured losses during sampling/dilution
3. Examples of experiments with
   high-T probe
4. CFD Simulation of aerosol dynamics in the
   probe
5. Conclusions

- Background: Porous tube dilution systems
  - Used for diluting, cooling and stabilizing the sample suitable for aerosol analyzers
  - Two (or three) different approaches:
    1. **Simulate dilution of combustion emissions in ambient air**
       - Important for emission measurements in small scale combustion units -> the behaviour of semivolatile organic compounds
    2. **Quench the sample to prevent losses and changes in the sample**
       - Fast dilution & cooling
       - Aims to stop chemical and physical changes in the sample
       - The problem with condensable vapours
    3. **Just measure the total particulate matter in hot gas - including the vapour-phase precursors**
       - For example determination of total alkali metal concentration in combustion furnace before heat exchangers or in small scale combustion before volatile organics condense
       - Sample cooling without significant thermophoretic losses is essential

- High- to Medium T porous tube quench probe

  - Dilution gas acts as a sheath flow to prevent wall losses
  - Sample cooling rates up to 10^6 $^oC/s$
  - High range of different dilution ratios can be used
  - The behaviour of consensable vapours is sensible to sampling conditions



UNIVERSITY OF EASTERN FINLAND

Particle losses during dilution in Venacontra - Dilution Aerosol Sampler (V-DAS)

Particle generation

- aerosol generator – TSI atomizer (TSI Aerosol Generator 3076)
- aerosol material – NaCl water solution
- particle concentration – number: ~4 x 10^5 #/cm^3
- particle size – GMD ~45 nm (polydisperse)

Dilution

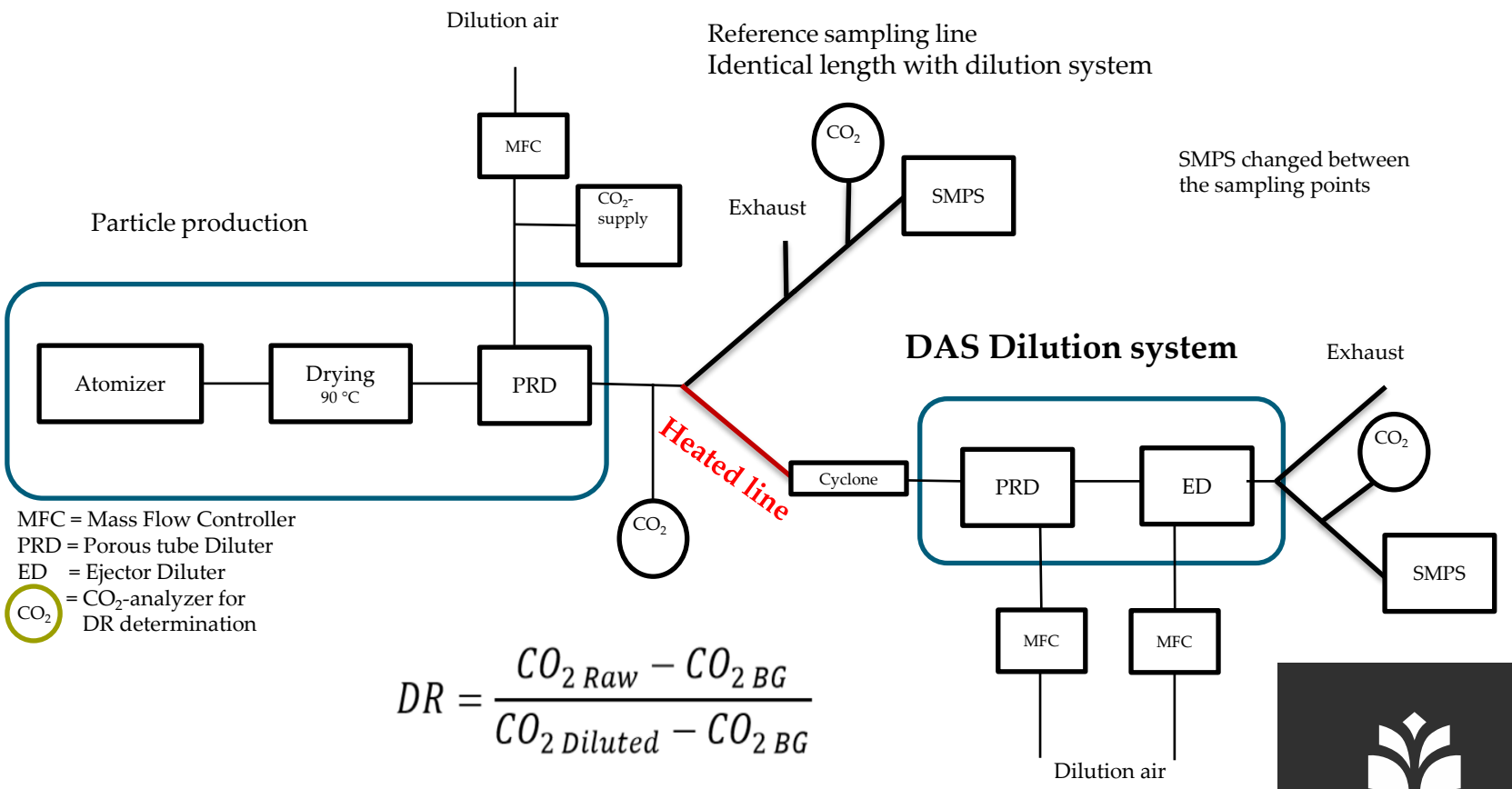
- feeding lines – 12 mm steel tubes
- sampling lines – reference line was also 12 mm steel tube
- dilution – heated probe (with cyclone), PRD, ED, sample splitter

Measurements

Results before and after dilution and steel pipe

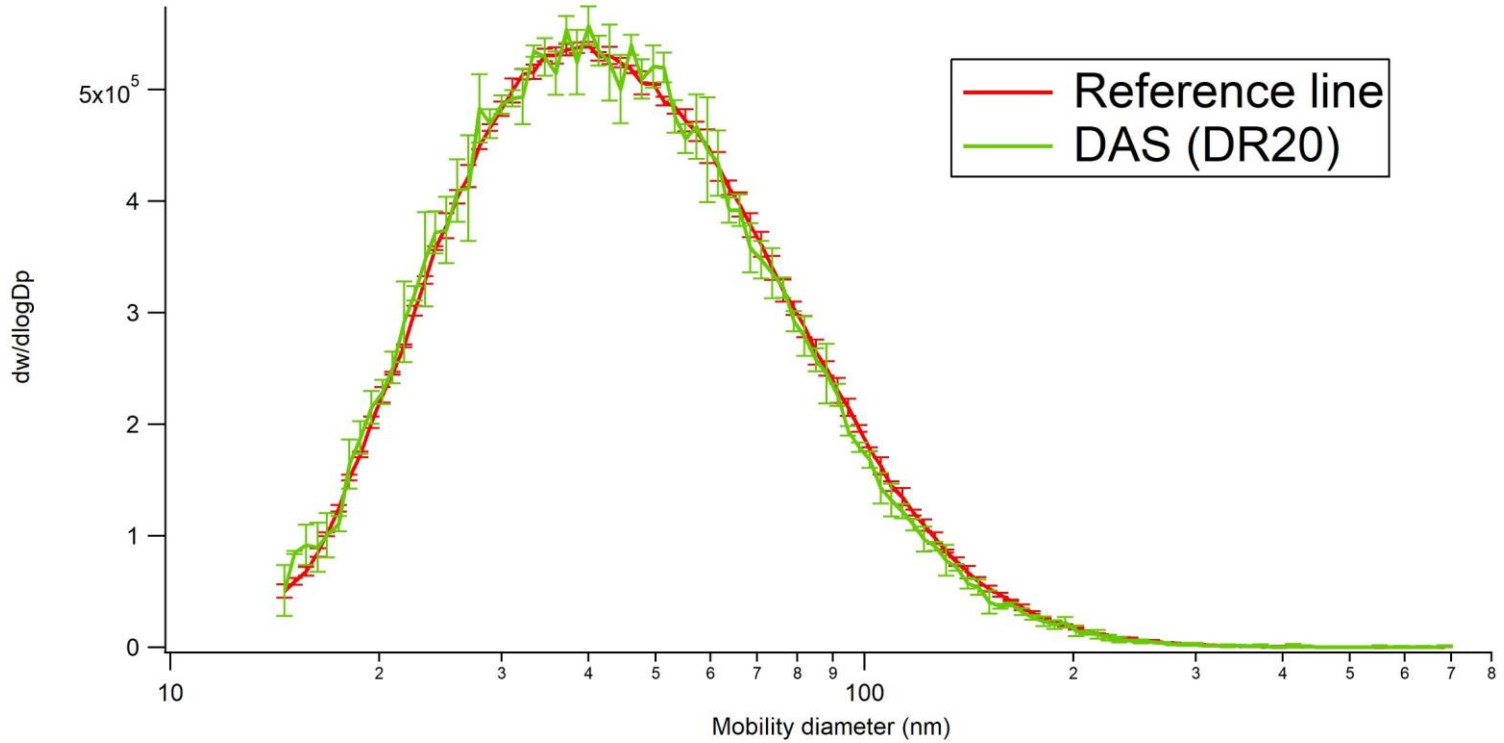
Standard deviations added to pictures

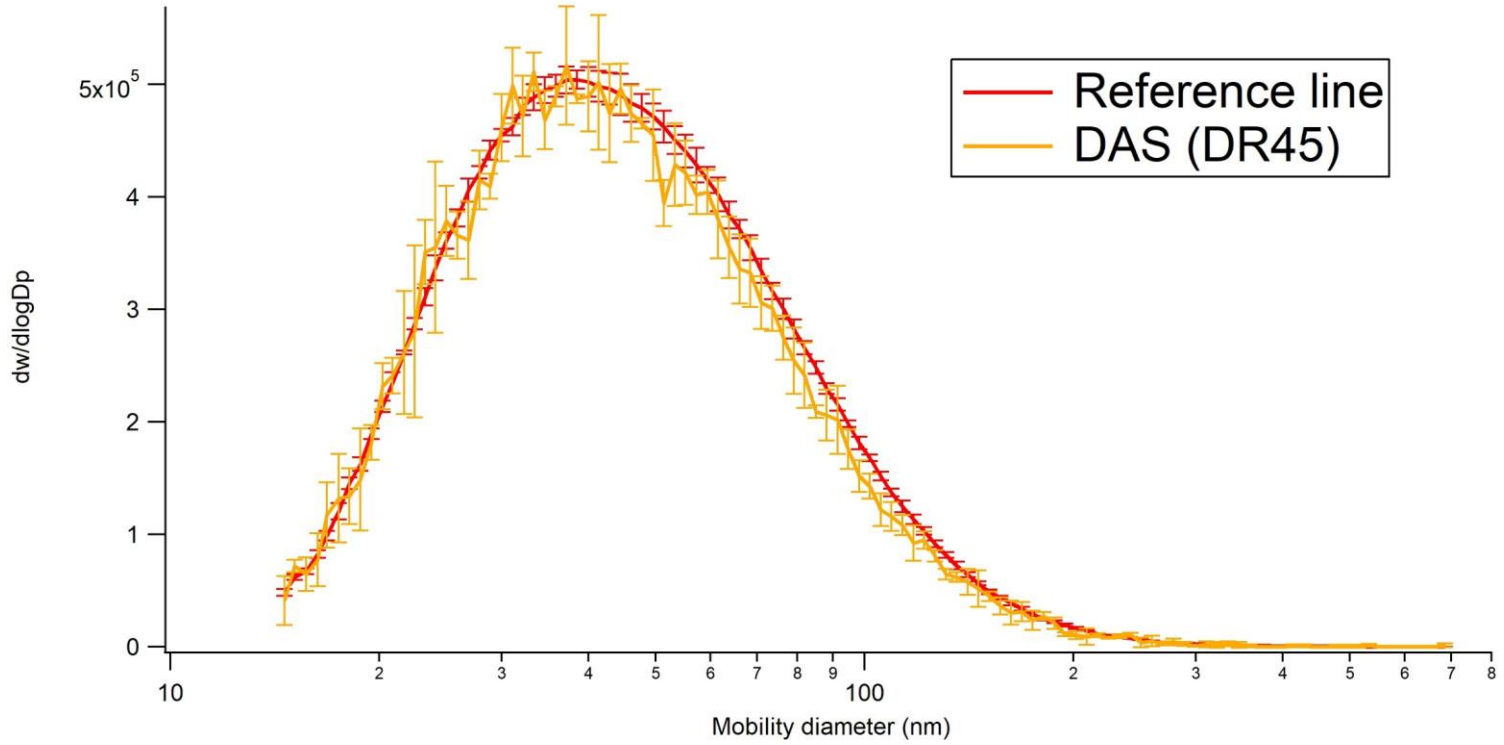
Particle losses during dilution - Dilution Aerosol Sampler (V-DAS)

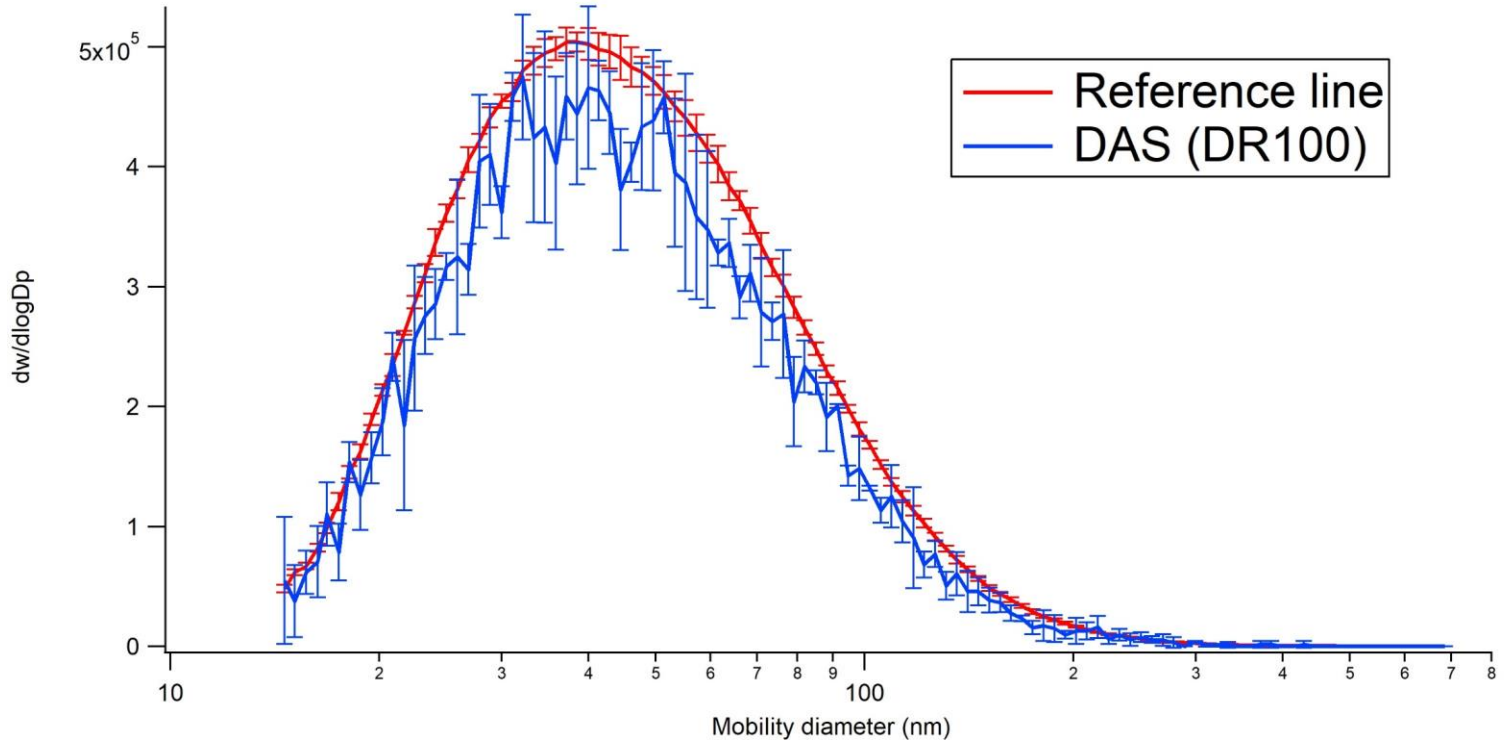


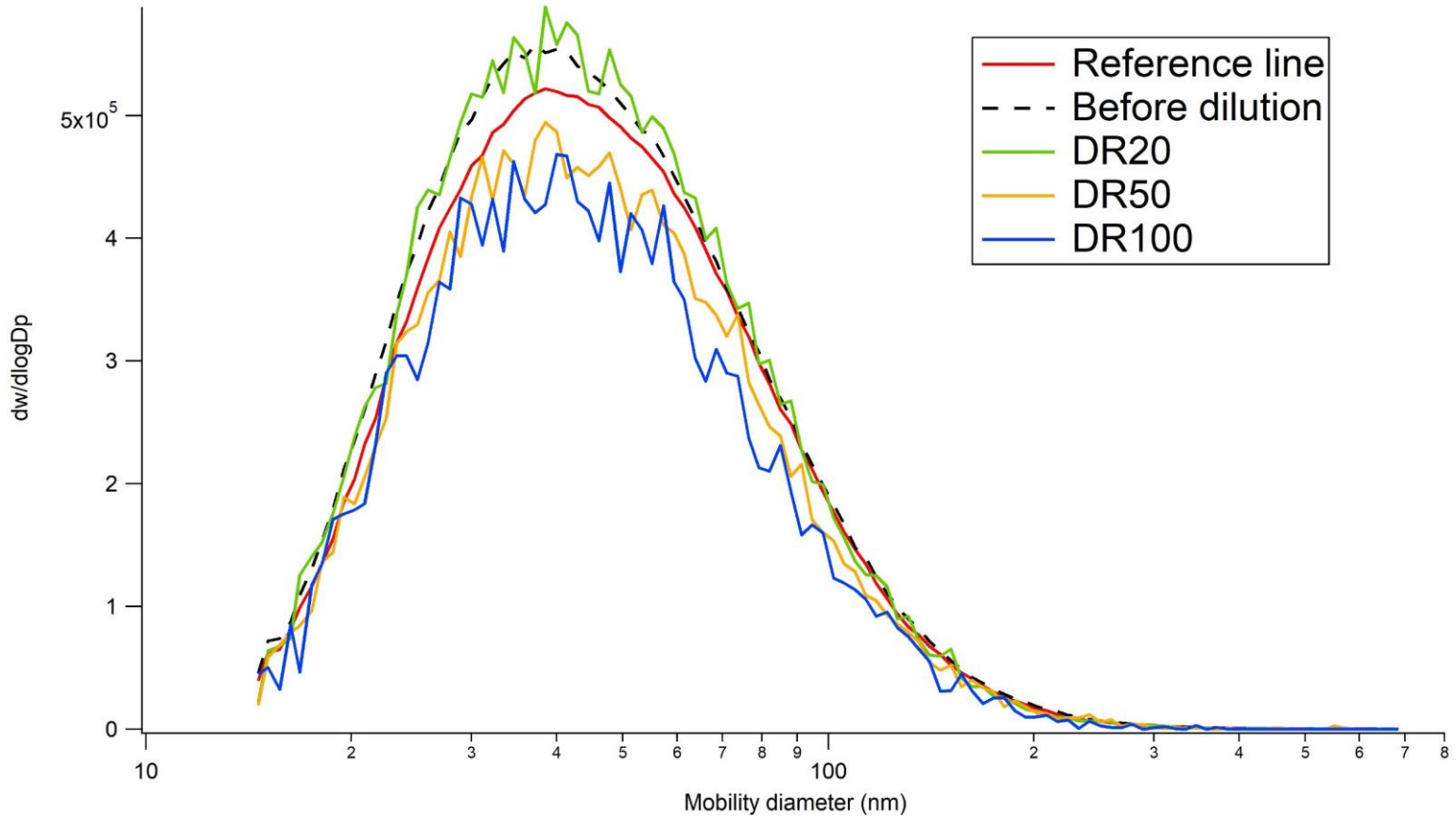
$$DR = \frac{CO_{2\,Raw} - CO_{2\,BG}}{CO_{2\,Diluted} - CO_{2\,BG}}$$

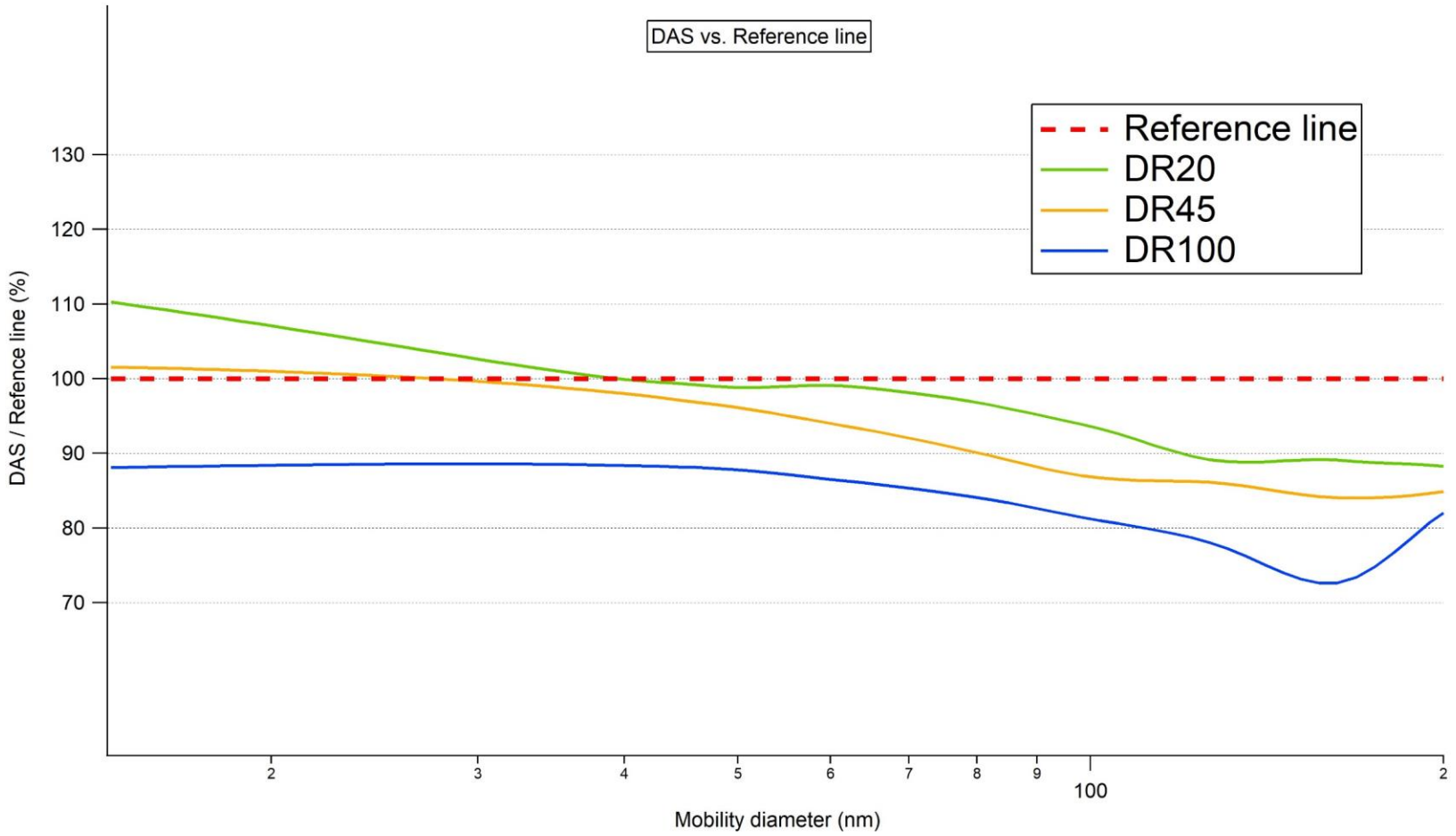
UNIVERSITY OF EASTERN FINLAND


Reference line
DAS (DR20)
dw/dlogDp
5x10^5
4
3
2
1
0
10
2
3
4
5
6
7
8
9
100
2
3
4
5
6
7
8
Mobility diameter (nm)


Reference line
DAS (DR45)
dw/dlogDp
5x10^5
4
3
2
1
0
10
2
3
4
5
6
7
8
9
100
2
3
4
5
6
7
8
Mobility diameter (nm)


5x10^5
4
3
2
1
0
dw/dlogDp
10
2
3
4
5
6
7
8
9
100
2
3
4
5
6
7
8
Mobility diameter (nm)
Reference line
DAS (DR100)


Reference line
Before dilution
DR20
DR50
DR100
dw/dlogDp
5x10^5
4
3
2
1
0
10
2
3
4
5
6
7
8
9
100
2
3
4
5
6
7
8
Mobility diameter (nm)


DAS vs. Reference line
Reference line
DR20
DR45
DR100
DAS / Refence line (%)
130
120
110
100
90
80
70
2
3
4
5
6
7
8
9
100
2
Mobility diameter (nm)

REMARKS

Why there seem to be larger losses when DR is 50 or 100?

- Errors when dilution factor is determined at high dilution cases

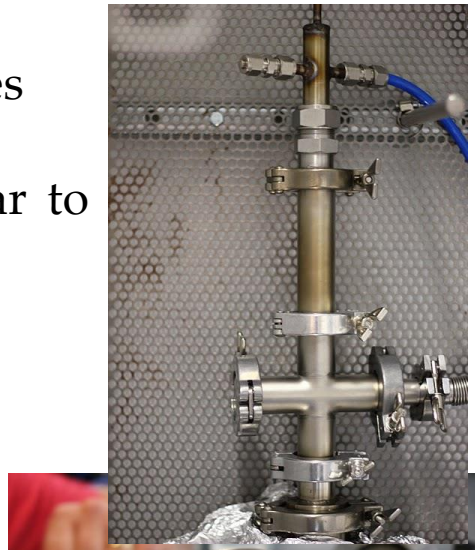
- The concentration measurements after high dilution are near to detection limits

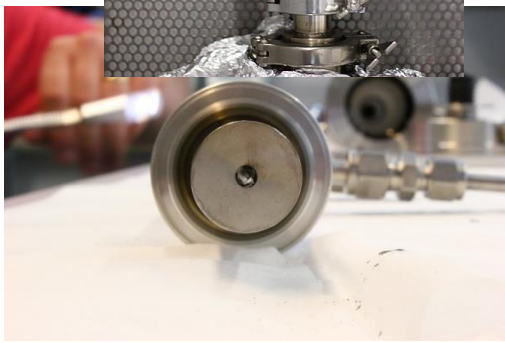
- Deviations when measurement are repeated

- Stability of particle generator

- Very samall amount of large particles → determination of large particle concentration

- SMPS returns very slowly from high to low concentration





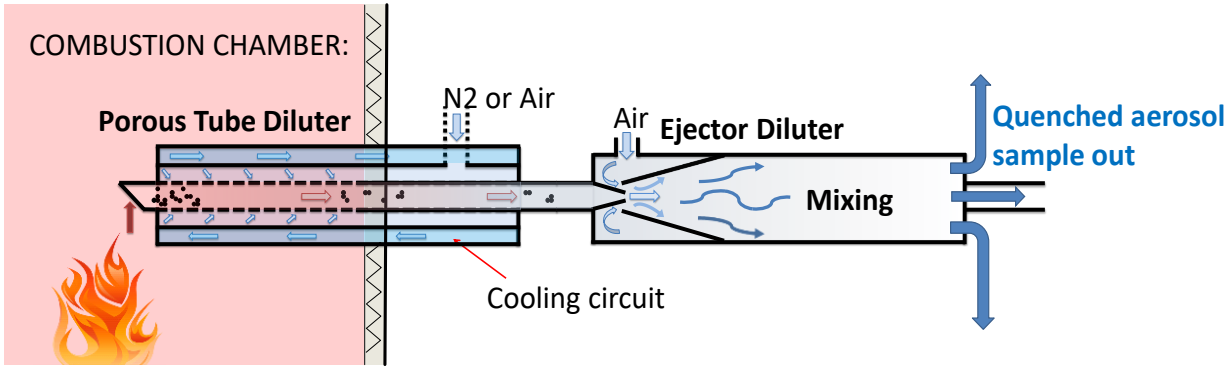
• Experiments with wood boilers

• The measurements were carried out at the University of Eastern Finland with a 40 kW grate combustion reactor and at the Karlsruhe Institute of Technology with a 100 kW wood boiler and in the KLEA batch combustion reactor.

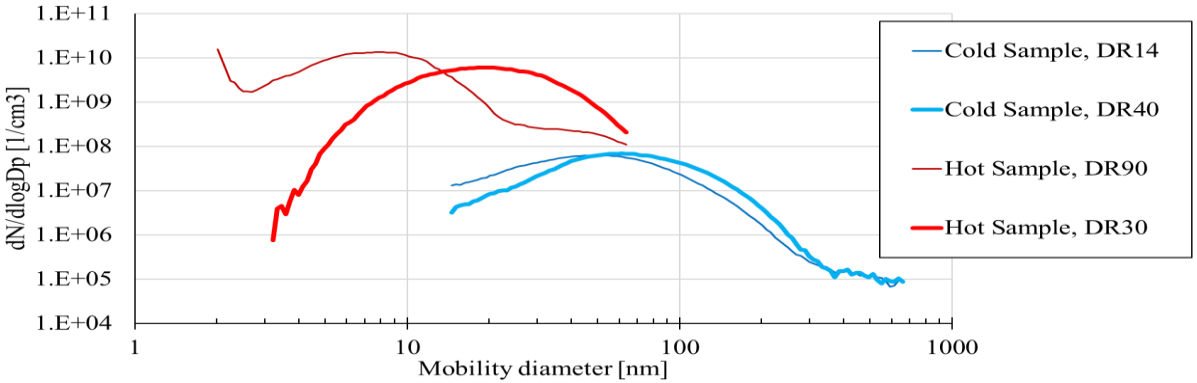
•All units were fired with wood chips. The samplings were carried out after the heat exchanger (T<200 ^{o}C), before heat exchanger (T≈600 ^{o}C) and directly from the combustion chamber (T=800-1000 ^{o}C).

•The diluting probe was water cooled and operated with varying dilution ratios, ranging from 14 to 120.

• The diluted sample was measured using a Scanning Mobility Particle Sizer and an Electrical Low Pressure Impactor.



Principle of operation in the high-temperature sampling system



Particle number size distributions (SMPS) measured after the heat exchanger (**T < 200 ºC**) and directly from the combustion chamber (**T=800-900 ºC**).

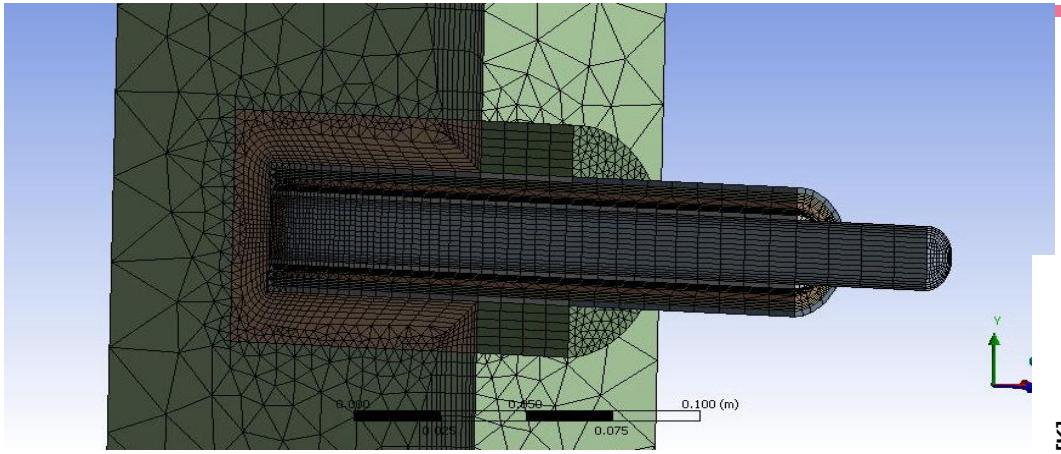
• Results

• PSDs measured directly from the combustion chamber at about 800-900 ^{o}C were very sensitive to dilution ratio, indicating that aerosol dynamic processes (condensation, coagulation, nucleation) were still ongoing in the sampling position and continued in the probe.

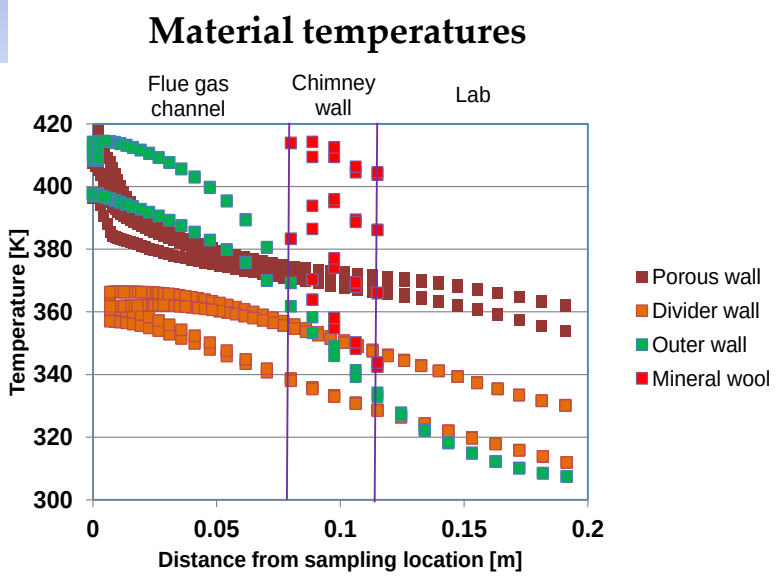
•The very high number concentration and small particle size is consistent with thermodynamic considerations, indicating that from the major chemical species only zinc oxide and possibly alkali sulfate is in the condensed phase and should exist as freshly formed seed particles at this temperature.

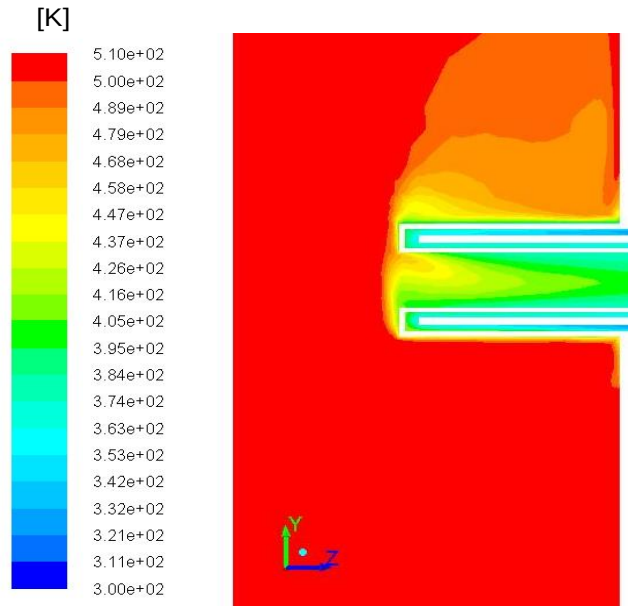
•The difference between hot and cold sampling agrees well with coagulation expected within the residence time between the sampling points.

• The nucleation mode is evidently formed from alkali metal chlorides inside the probe.



Computational grid for the system where the porous tube is directly inserted in the flue gas channel (Ansys-Fluent)



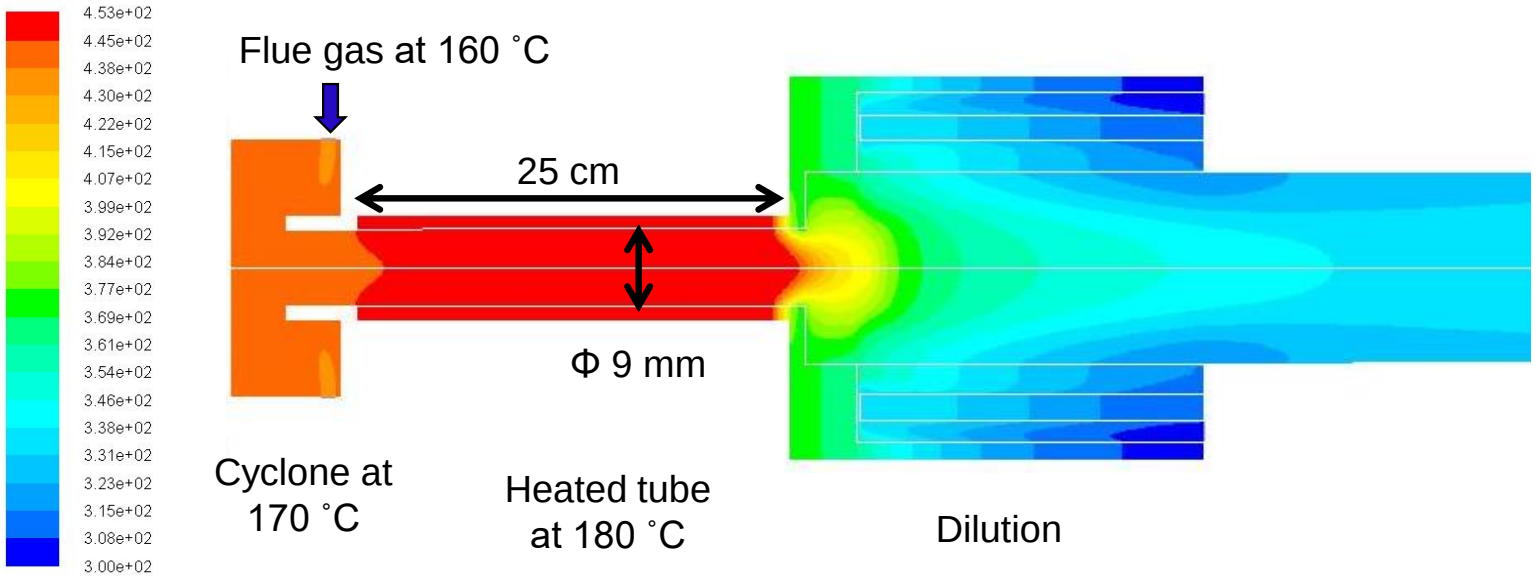


Gas temperature profiles

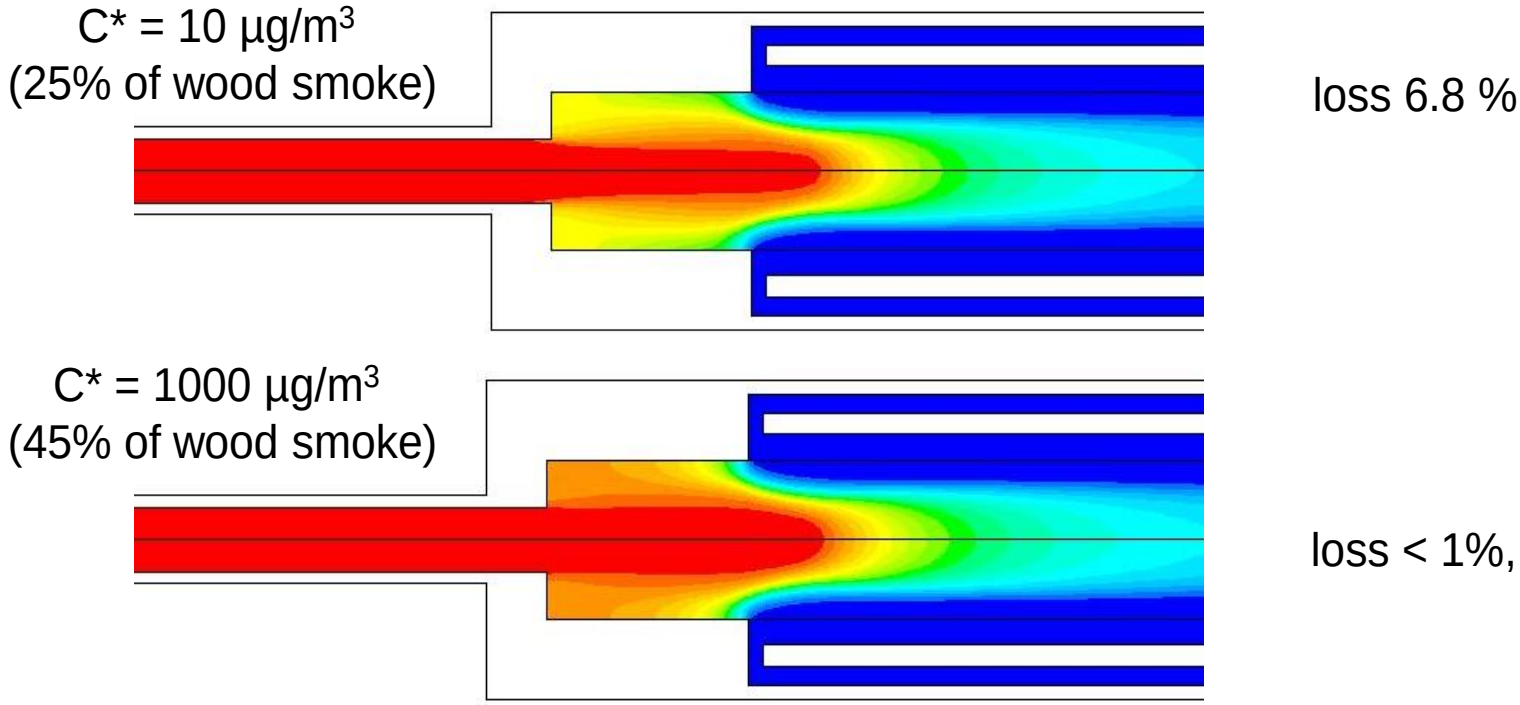
Small scal combustion: CFD-modelling of Organic vapours

UNIVERSITY OF EASTERN FINLAND

The porous tube flow as temperature contours. Most of the dilution takes place in the first half of the porous tube.



As the time lag to achieve a steady-state temperature distribution turned out to be a drawback of the system discussed above, a new design was taken into consideration. **A heated line** of tube that precedes the porous tube diluter provides a remedy to the lack of explicit heat control.



Contours of organic vapour concentration of two vapour pressure fractions at the connection of the heated tube and the porous tube section. The colour scale is such that the red colour represents the respective concentration in the undiluted flue gas.

CONCLUSIONS

- **The porous tube quench probe was found to reproduce:**
  - Relatively fast mixing and dilution close to the probe tip
  - High number concentrations and small particle size due to less coagulation/agglomeration (than in conventional sampling)
  - Different behaviour of condensable vapours depending on the sampling parameters and sample properties
    - The surface area of the ”seed” particles, mixing and cooling are factors that mostly affect on the formation of nucleation mode.
    - Optional ways to enhance the performance:
      1. Increase cooling rate
      2. Pre-heated tube before dilution → **Heated line**
- **CFD aerosol dynamics model was used to predict and optimize vapour deposition on walls**
  - supports the design of sampling probes for various conditions / purposes
  - particle deposition is minumal (<1%) and vapour deposition can be minimised by CFD design.
- A lot of experience on small scale combustion measurements including on-line control of the dilution parameters (SIMO/UEF/Dr. Jarkko Tissari and Venacontra Ltd./Dr. Mika Ihalainen)

Thank you for attention!

Acknowledgements:

- FINE laboratory staff
- Dr. Jouni Pyykönen for CFD (VTT) simulations
  - Strategic funding by UEF
  - Business Finland
  - ERANET project EN-PME-TEST
  - Venacontra Ltd.

Real-LIFE Emissions

The Real-Life Emissions project has received funding from the European Union under grant agreement n° LIFE 20 PRE/FI/000006

Life