VSL

Dutch Metrology Institute

IMPRESS II – WP3: Flow Uncertainty and Impact on Annualised Mass Emissions

Overview of the work package

VSL, NPL, ISSI, CMI, TU Delft, CNR

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WP3: Relevant standards

- This work package deals with flow rate measurement of emissions, primarily focused on relatively narrow stacks.
- Reference method for emission flow measurement:
  - EN ISO 16911-1 and EN ISO 16911-2 Stationary source emissions — Manual and automatic determination of *velocity* and *volume flow rate* in ducts
    - Part 1: Manual reference method
    - Part 2: Automated measuring systems (refers to Part 1 for calibration)
  - EN 15259 Air quality. Measurement of stationary source emissions. Requirements for measurement sections and sites and for the measurement objective, plan and report
    - Sets requirements for the sampling plane and sampling points (tangential method required)
- How well does the reference method perform in narrow stacks?

WP3: ISO 16911-1

- Provides a method for the determination of gas velocity and volume flow rate within an emission duct
- Describes a method to determine the velocity profile of the gas flow across a measurement plane in the duct
- Gives a method to determine the total volume flow rate at a measurement plane in the duct based on a grid of point velocity measurements (typically done with Pitot tubes)
- Described alternative methods: tracer dilution, tracer transit time, and by calculation from energy consumption

The volume flow rate, q_V, is determined by multiplying the average velocity by the area of the measurement plane (i.e. the internal area of the duct at the measurement plane).

$$q_V = \bar{v}_p A \quad (1)$$

where

$\bar{v}_p$ is the average of the point velocity measurements;

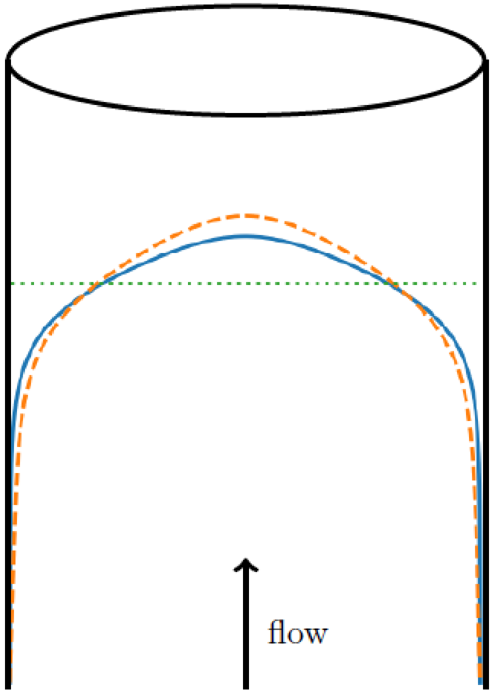
A is the area of the measurement plane.

WP3: EN 15259 requirements

b) measurement plane shall be situated in a section of the waste gas duct (stack etc.) where homogenous flow conditions and concentrations can be expected;

NOTE 4 The requirement for homogeneous flow conditions is generally fulfilled if the measurement plane is

- as far downstream and upstream from any disturbance, which could produce a change in direction of flow (e.g. disturbances can be caused by bends, fans or partially closed dampers),
- in a section of a duct with at least five hydraulic diameters of straight duct upstream of the sampling plane and two hydraulic diameters downstream (five hydraulic diameters from the top of a stack; see A.2) and
- in a section of a duct with constant shape and cross-sectional area.



Homogenous?

WP3: EN 15259 requirements

c) measurements at all the sampling points defined in 8.2 and Annex D shall prove that the gas stream at the measurement plane meets the following requirements:

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Table 2 — Minimum number of sampling points for circular ducts

Range of sampling plane areas m^2	Range of ducts diameters m	Minimum number of sampling lines (diameters)	Minimum number of sampling points per plane
< 0,1	< 0,35	–	1 [a]
0,1 to 1,0	0,35 to 1,1	2	4
1,1 to 2,0	>1,1 to 1,6	2	8
> 2,0	> 1,6	2	at least 12 and 4 per m^2 [b]

a Using only one sampling point can give rise to errors greater than those specified in this European Standard.

b For large ducts, 20 sampling points are generally sufficient.

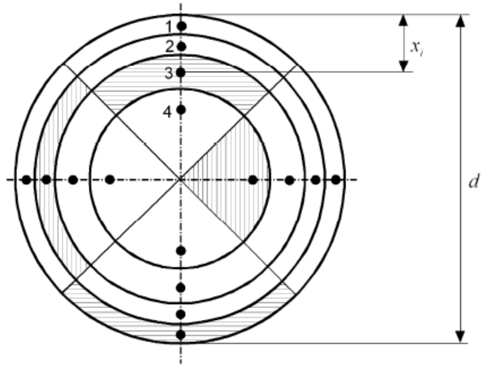
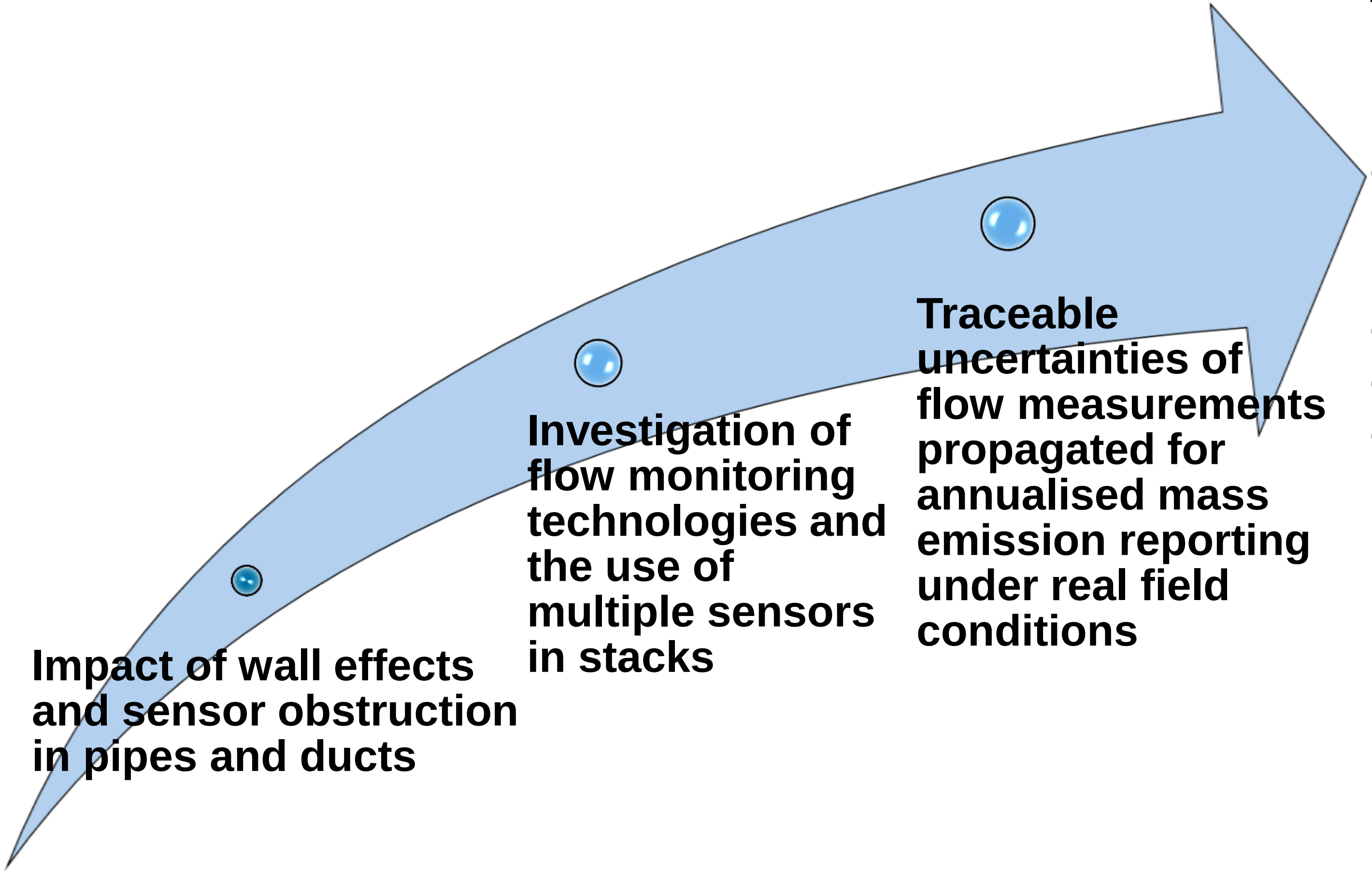


Figure D.2 — Sampling point positions in circular ducts – Tangential method (showing positions for ducts over 2 m diameter)

WP3: Goal



To determine the uncertainties and provide traceability of mass emission measurements related to flow calibrations carried out in field conditions

WP 3: Flow uncertainty and impact on annualised mass emissions

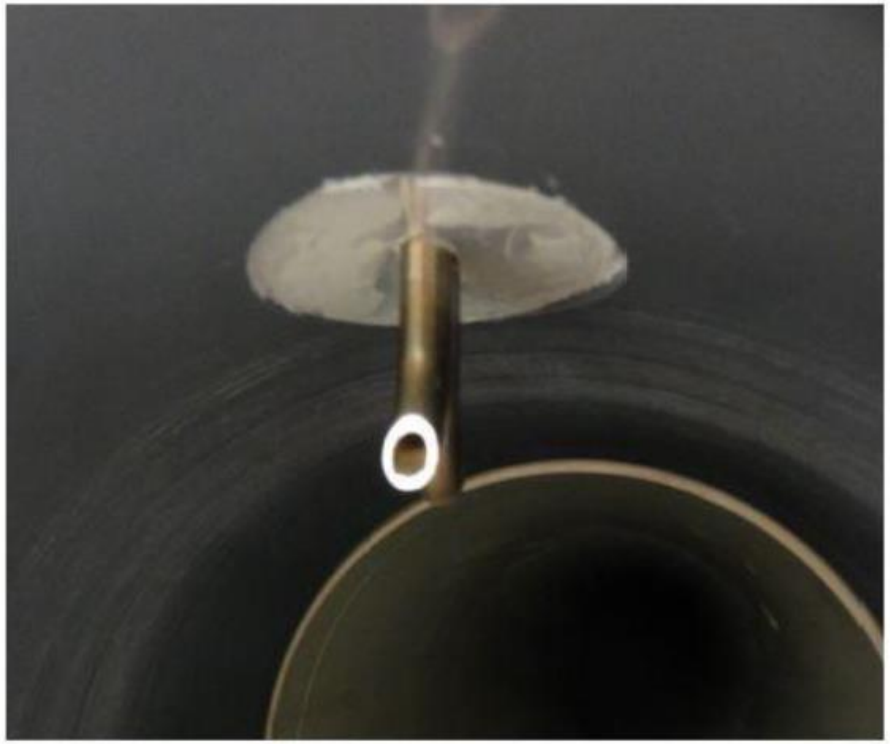
- Task 3.1: Traceable uncertainties of flow measurements propagated for annualised mass emission reporting under real field conditions
  - Evaluation of uncertainty sources and modelling by NPL
- Task 3.2: Impact of wall effects and sensor obstruction in pipes and ducts
  - Experiments by VSL
  - Simulations by TU Delft
- Task 3.3: Investigation of flow monitoring technologies and the use of multiple sensors in stacks
  - Effects of flow disturbances
    - Experiments by VSL
    - Simulations by CMI
  - Using different flow monitoring techniques
    - Measurements/comparisons by CNR & ISSI

Task 3.2: Impact of wall effects and sensor obstruction in pipes and ducts

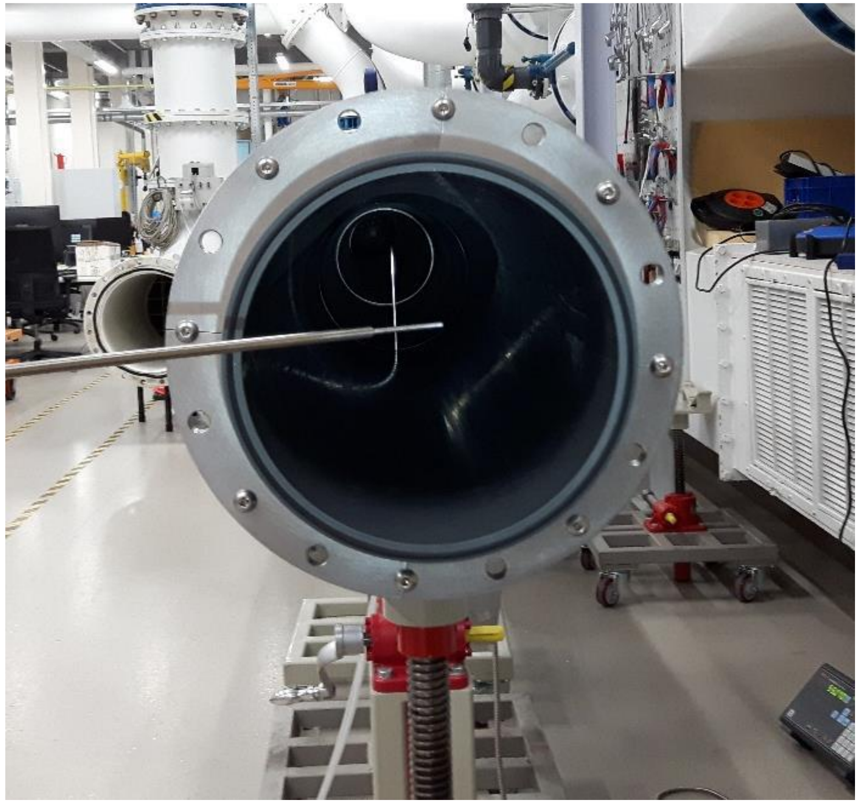
- Experiments by VSL:
  - Sensor obstruction effects:
    - Part of the duct is blocked by the pitot tube, what is the uncertainty and error associated to that?
    - Calculations based on experimental parameters
  - Measurements to determine wall effects
    - Using S- and L-type pitot tubes at various distance from the wall in “ideal” conditions
    - Calculation of known corrections for L-type pitot tubes
    - Comparing experiments to theoretical prediction of the flow profile

- Simulations by TU Delft:
  - Numerical simulations with OpenFOAM to obtain flow profiles at relevant Reynolds numbers
  - Predictions for S-Pitot measurements

Task 3.2: Experiments



S-Pitot

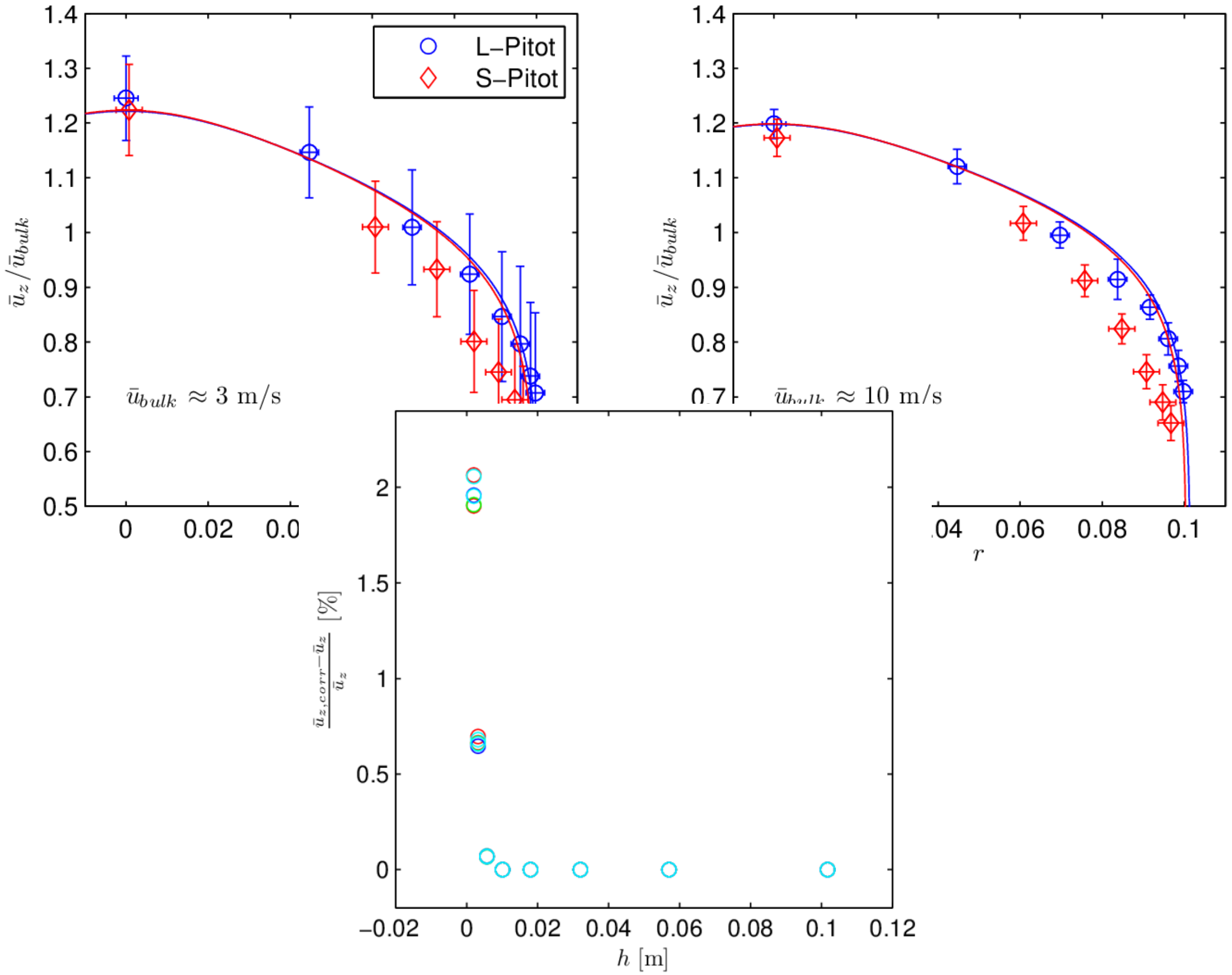


L-Pitot

Both cases >10 hydraulic diameters of straight duct upstream of the Pitot tube

Task 3.2: Experimental results

- Wall effects:
  - S-Pitot tubes have a tendency to underreport near the wall, but above 5 cm distance from the wall (required by standards), there is no notable difference.
  - Known corrections for L-Pitot tubes are small and not always easily calculated (see e.g. [1,2])
    - 2% correction for the case where the L-pitot was laying flat on the duct wall
    - Negligible when more than a cm away from the wall



[1] F. A. MacMillan, "Experiments on Pitot-tubes in shear flow", 1956
[2] B. J. McKeon et al., "Pitot probe corrections in fully developed turbulent pipe flow", 2003

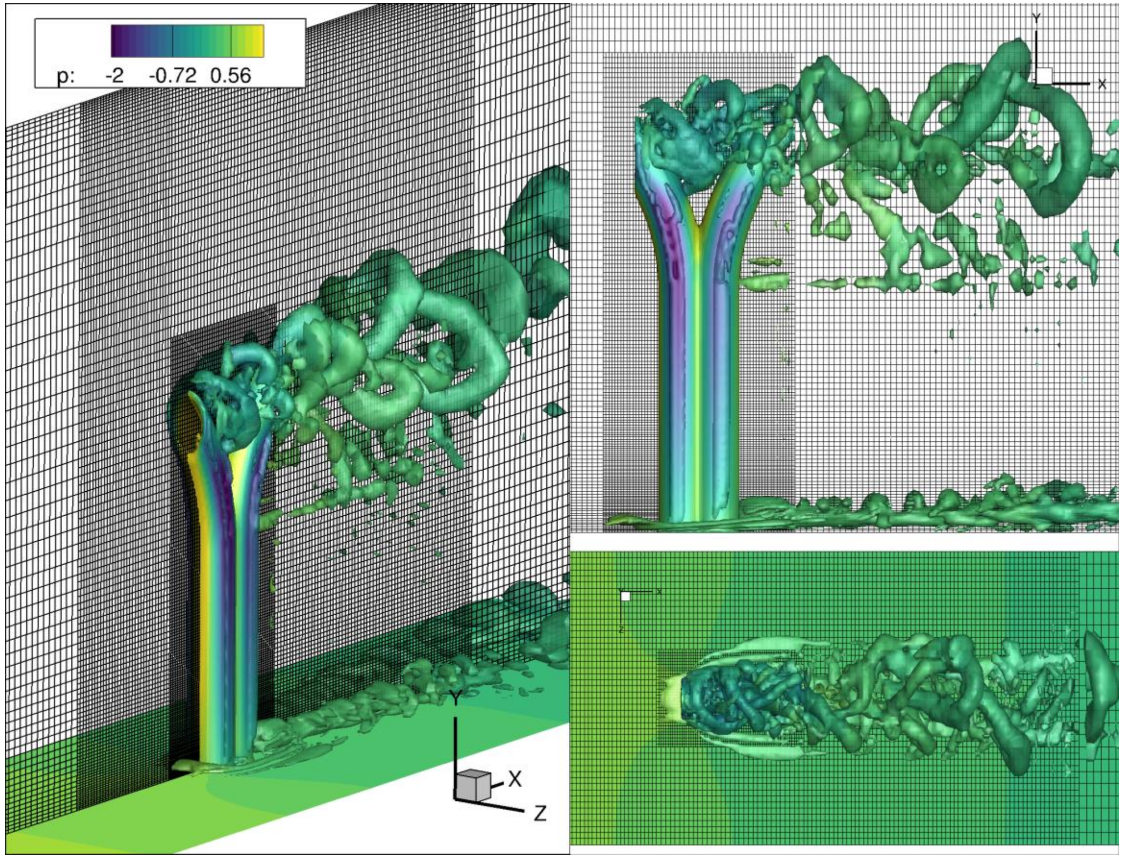
Task 3.2: Experimental results

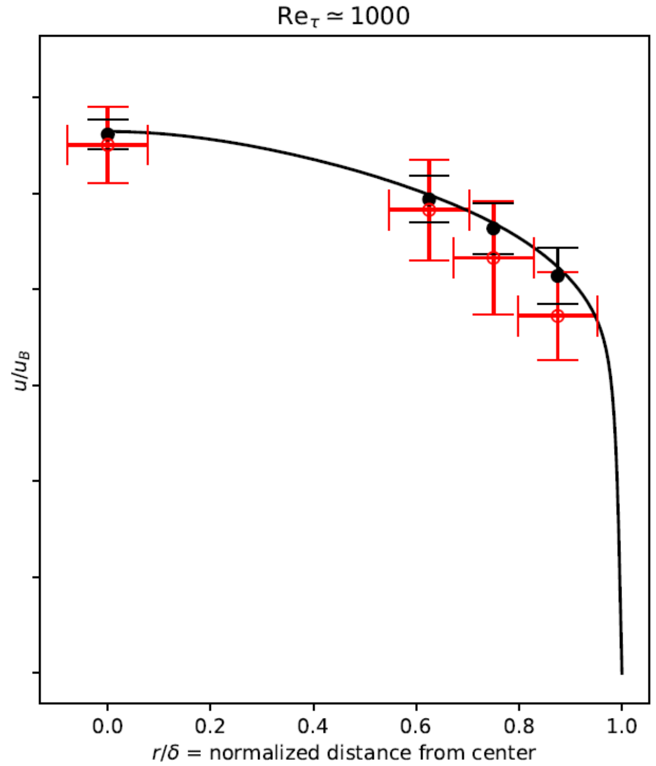
- Sensor obstruction effects:
  - Corrections can be made for S-Pitot tubes, correction factor:
    - $\frac{A - A_{pitot}}{A}$
  - Effects are typically small compared to the total measurement uncertainty

Bulk velocity	Uncorrected velocity	Corrected velocity
$\bar{u}_{bulk}$ [m/s]	$\bar{u}_z$ [m/s]	$\bar{u}'_z$ [m/s]
3.14	3.87±6.4%	3.80±7.6%
4.75	5.80±4.3%	5.69±5.8%
7.56	8.97±2.4%	8.80±4.7%
9.67	11.42±2.2%	11.20±4.5%

Task 3.2: Numerical results

- Flow around S-Pitot tube successfully simulated
- Also here it is found that S-Pitot tubes have a tendency to underreport the velocity





WP 3: Flow - summary

- WP3 successfully completed
- 1 MSc thesis delivered
- 3 papers were written of which 2 are already published (open access!):

Technical Paper

Narrow stack emissions: Errors in flow rate measurement due to disturbances and swirl

Stanislav Knotek, Marcel Workamp, Jan Geršl & Menne D. Schakel

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Open Access Article

Spectroscopic Techniques versus Pitot Tube for the Measurement of Flow Velocity in Narrow Ducts

by Francesco D'Amato [1], Silvia Viciani [1,*], Alessio Montori [1], Marco Barucci [1], Carmen Morreale [2], Silvia Bertagna [2] and Gabriele Migliavacca [2]

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- Using both experiments and models, much insight was gained into the uncertainties of emission flow measurement, particularly for narrow stacks.