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Cyclonic stack flow measurement uncertainties and impact on annualised mass emission measurements

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Abstract

Measurements of emissions of air pollutants are typically performed in accordance with CEN standards, which are being referred to as Standard Reference Methods. To determine emissions of air pollutants, concentration and flow measurements need to be performed within the stack. Standard EN ISO 16911-1 is employed as the Standard Reference Method for flow measurements. We perform validation measurements for this method in narrow stacks with cyclonic flows. To traceably determine the uncertainty of cyclonic flow in realistic field conditions, we use a stack simulator. We use a traceably calibrated wind tunnel to provide the stack with a well-defined input flow. We perform velocity measurements with a traceably calibrated L-Pitot tube in a stack simulator with two configurations: one with a straight stack entrance, the other with an elbow just before the stack entrance. In both cases, we measure the velocity at planes at several hydraulic diameters downstream from the stack entrance, namely 3, 4, 5, 6, and 7 diameters downstream of the stack entrance. We also characterize the velocity profile at the stack entrance. We show that in both configurations, the flow profile deviates significantly from fully developed turbulent pipe flow, even at 7 diameters downstream of the stack entrance. In case of cyclonic flow, the effect is more pronounced. Future work will focus on comparing the flow measurements with computational fluid dynamics modelling to gain further insight into the additional flow measurement uncertainty.

1. Introduction

Pollutants are becoming an increasingly large environmental and health hazard. Recently, new European legislation has been introduced to continue to drive down emissions, containing increasingly stringent emission limit values. Emission limits are enforced by measurements, legally required to adhere to CEN standards, typically being referred to as Standard Reference Methods. Standard EN ISO 16911-1 is employed as the Standard Reference Method for flow measurements [1]. This standard also refers to EN 15259 [2] which sets requirements for measurement sections and sites, including requirements for the measurement plane when determining the average velocity from a grid of point flow measurements (e.g. using a Pitot tube).

One of these requirements is that the “measurement plane shall be situated in a section of the waste gas duct (stack etc.) where homogenous flow conditions and concentrations can be expected”, for which it is noted that this requirement is generally fulfilled 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, if this section is of constant shape and free of any disturbances. However, the field validation trials for EN ISO 16911-1 were carried out at plants with no significant cyclonic flow [3]. Cyclonic flow (turbulent flow with a significant amount of swirl) may arise when a flow is making consecutive turns, such as an elbow before a stack entrance. Part of the EN ISO 16911-1 requirements is thus poorly validated in stacks with cyclonic flow, although the standard does provide a velocity correction formula which accounts for the tangential component of non-axial flow in case of significant swirl (swirl angle >15°).

We perform experiments in a narrow stack simulator to investigate the effect of flow disturbances on emission measurements. The stack has two configurations, one with a straight entrance via a T-junction, while the other has an additional elbow, which generates swirl in the vertical stack. We show that in both cases, the flow profile deviates significantly from a fully developed profile, even at seven hydraulic diameters downstream of the T-junction. Future work will combine computational fluid dynamics (CFD) simulations with our measurements to gain additional insight to emission measurement uncertainties.

2. Experimental

We perform experiments in a stack simulator. The stack is a vertical pipe with a diameter of 0.2034 m. The stack has a blunt closed bottom, and the flow enters the stack through a T-piece, of which the horizontal tube is connected to a traceably calibrated wind tunnel via a cone-shaped connector. We use the stack simulator in two configurations: one with a straight stack entrance, the other with an elbow just before the stack entrance. For an overview of the two configurations of the stack simulator, see Figure 1.

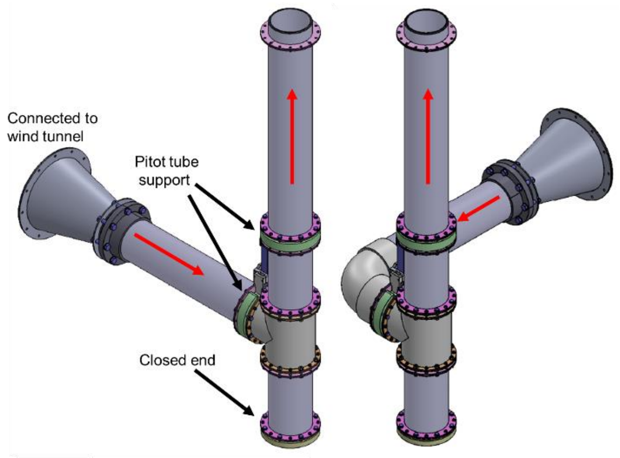

Figure 1: Overview of the two configurations of the stack simulator. Red arrows indicate the flow direction. Green parts represent the mounting ring of the Pitot tube support (Figure 2).

We use a traceably calibrated L-Pitot tube (AIRFLOW developments, UK) to perform the velocity measurements. The Pitot tube is held in place using a specially designed support, equipped with a hand-controlled linear stage (Mitutoyo, Prod. Nr. 539-803) with a digital readout, allowing to precisely position the Pitot tube at various radial positions in the stack. The Pitot tube support is mounted to a ring of which there are two in our stack simulator (Figure 2). For an overview of the Pitot tube support holder and mounting ring, see Figure 2.

The mountings rings are made such that, after loosening the bolts holding it in place, the ring is freely rotatable, allowing measurement at different measurement lines without disassembling the stack simulator. The mounting rings are placed in two positions: one at the entrance of the T-junction, the other in the stack downstream of the T-junction. By using variable lengths of pipe, the latter was placed at 3, 4, 5, 6, or 7 diameters downstream of the stack entrance. As we use only one Pitot tube but two mounting rings, the hole for the Pitot tube on the mounting ring that is not in use, is sealed with a plug that sits flush with the inner surface of the ring.

We perform experiments at two different volumetric flow rates Q corresponding to bulk velocities $v_{bulk} = Q/A$ of 5.0 and 10.0 m/s, where A is the cross-sectional area. Due to the use of the calibrated wind tunnel, the expanded uncertainty in Q does not exceed 0.15%.

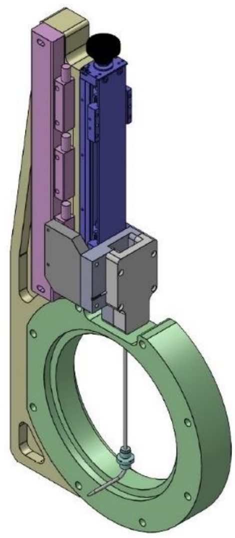

Figure 2: Overview of the Pitot tube support and mounting ring.

3. Uncertainty sources

3.1 Uncertainty of the velocity measurements

The axial velocity in the stack is measured using an L-Pitot tube, traceably calibrated in a wind tunnel. As we are interested in the velocity profile, we compute the non-dimensional axial velocity $v_z^* = v_{measured}^*/v_{bulk}^*$, at standard laboratory conditions (denoted by asterisks). The uncertainty in the average non-dimensional velocity $\bar{v}_z^*$ has several uncertainty sources including:

- Pitot tube constant
- diameter of the pipe
- differential pressure
- atmospheric pressure
- temperature
- volumetric flow rate

We measure the velocity three times so that the uncertainty related to repeatability is also estimated.

3.2 Uncertainty in radial position of the Pitot tube

We determine the radial position of the Pitot tube using the digital readout of the linear stage. The uncertainty in the (radial) position of the Pitot tube originates from various sources. The largest uncertainty sources are:

- Play between the pipe and the mounting ring
- Imperfections in the straightness of the Pitot tube
- Definition of the zero point (i.e. the position at which the Pitot hits the wall)

The uncertainty related to the accuracy of the linear stage is negligible. Note that there's also an uncertainty in the angle of the Pitot tube support, which is estimated at 3 degrees (k=2).

4. Results & Discussion

We characterize the flow by measuring the average non-dimensional axial velocity $\bar{v}_z^*$ at measuring planes spaced 3, 4, 5, 6, and 7 hydraulic diameters downstream of the stack entrance. At each plane, we measure the velocity in two perpendicular measurement lines (x- and y-axes), corresponding to four different positions/angles of the Pitot tube mounting ring (the centre of the stack is sampled four times). Measurement points are chosen such that the distances from the wall are spaced logarithmically, see Figure 3.

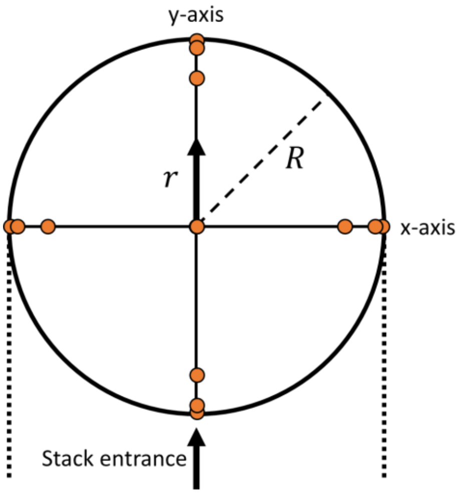

Figure 3: Top view of the measurement plane. The y-axis is parallel to the axis of the stack entrance. The radial position of measurement point is denoted by r while the tube radius is given by R. Orange points denote the measurement positions.

In Figure 4 we plot the results of the input profile measurements, for the case with a straight entrance (a) and with an elbow before the entrance (b). In the first case, the profile is very flat, in agreement with our expectations, as the stack is connected to our wind tunnel which generates a flat profile. A relatively small effect can be observed: the measurements along the y-axis are slightly asymmetric. This agrees with expectations as well because the stack is closed at the bottom while it is open at the top. For the case with the elbow just before the entrance, we observe a very asymmetric profile, as a result of the bend. In agreement with expectations, the velocity is decreased in the section of duct directly after the inside of the elbow, while the outside has increased velocity.

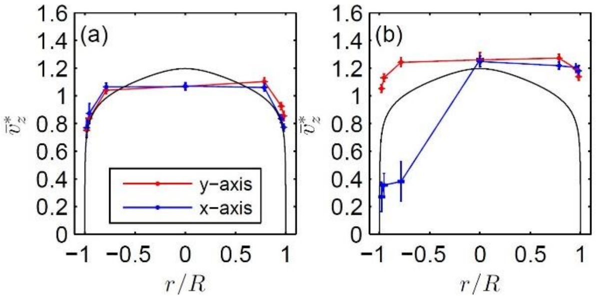

Figure 4: Average non-dimensional axial velocity $\bar{v}_z^*$ as a function of r/R, for a stack with a straight entrance (a) and a stack with an elbow before the entrance (b), measured at the entrance of the T-junction. Solid black lines represent the Gersten-Herwig reference profile for fully developed turbulent pipe flow [6]. For these inlet measurements, the x-axis is along the horizontal line and the y-axis along the vertical line passing through the origin.

In Figure 5 we plot the results of measurements at 3, 5 and 7 hydraulic diameters downstream of the stack entrance, using v_{bulk} = 10.0 m/s. Results at 5.0 m/s display similar trends (not shown). In the stack with the straight entrance, at 3 diameters downstream (Figure 5a), there's a large velocity depression at the side of the stack entrance, while at the opposite side the velocity is increased, in agreement to simulations of bigger stacks [5]. When looking further downstream (Figure 5b+c), the flow slowly becomes more axially symmetric, and approaches the reference profile for fully developed turbulent pipe flow as given by Gersten [6]. However, even at 7 hydraulic diameters downstream (Figure 5c), deviations from the reference profile exist. It is noteworthy that the profile does have a strong resemblance to the input profile (Figure 4a) at this plane.

In the case of the elbow before the stack entrance (Figure 5d-f) we observe highly asymmetric flow profiles. The flow profile remains highly asymmetric, even at 7 hydraulic diameters downstream of the T-junction (Figure 5f). The flow profile deviates significantly from the reference profile, as well the input profile, suggesting cyclonic effects could constitute a significant uncertainty source in mass emission measurements.

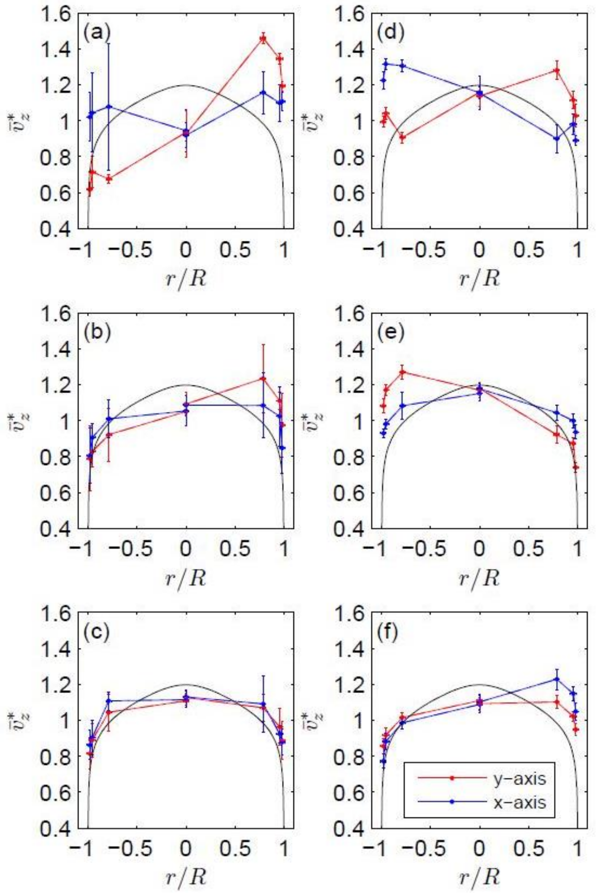

Figure 5: Average non-dimensional axial velocity $\bar{v}_z^*$ as a function of r/R, for a stack with a straight entrance (a-c) and a stack with an elbow before the entrance (d-f) at 3 (a+d), 5 (b+e) and 7 (c+f) diameters downstream of the T-junction. All data shown was recorded at v_{bulk} = 10.0 m/s. Legend in (f) applies to all panels. Solid black lines represent the Gersten-Herwig reference profile for fully developed turbulent pipe flow [6].

5. Conclusions

We develop a stack simulator to measure velocity profiles in narrow stacks using an L-Pitot tube. We present results of measurements in two configurations: one with a straight stack entrance and one with an elbow. The standard [2] suggests that 5 hydraulic diameters downstream of a flow disturbance, the flow can be considered "homogenous". We show that for our narrow stack simulator, the flow profile deviates from the velocity profile at the stack entrance and the reference profile for fully developed pipe flow, even at 7 hydraulic diameters downstream of the flow disturbance. The deviations are larger for the configuration with the elbow before the stack entrance, which generates cyclonic flow. These findings suggest that cyclonic flow not only increases the error of the flow rate measurement according to [1, 2] by presence of transversal velocity components and their impact on measurement error of a Pitot tube, but also by slower decrease with downstream pipe length of flow asymmetry introduced by the T-junction of the supply pipe. Future work will focus on determining the error of the Standard Reference Method [1] in conditions of cyclonic flow by direct comparison of the flow rate standard of VSL with flow rate measurements in the stack model according to [1, 2]. The measurement data from the stack model will be used to validate a CFD model providing a detailed computed velocity field in the stack which will be further utilised to predict the SRM error for various types of Pitot tubes with different swirl angle dependencies.

6. Acknowledgement

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