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Monte-Carlo modelling to demonstrate the influence of alternative flow reference techniques on annual mass emission uncertainty

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Abstract

Industrial emissions into the atmosphere are quantified by measuring the concentration and flow rate in a duct or stack prior to release. These measurements are combined to produce a mass emission which is reported to the European Pollutant Release and Transfer Register. These measurements have to be made according to standards to ensure that they are consistent and accurate. Uncertainty limits are set in relevant EU legislation which must be adhered to. The standard for flow measurement, EN ISO 16911, is in two parts covering manual reference methods and automated measuring systems (AMS). The former outlines six validated methods for calibrating an AMS, while the latter outlines the quality control system to be followed to meet the requirements of the legislation. However the standard does not provide consistent information on the impact of the different calibration methods on the uncertainty of the reported emissions. Here we model a system monitoring stack flow and pollutant concentration, including quality control procedures in EN ISO 16911. Several alternative reference methods are modelled to compare the effects of using these different techniques for calibration on the uncertainty of reported annual mass emissions. In a low uncertainty regime the L- and S-type Pitot provide the best performance for both constant and variable flows, however in higher uncertainty regimes all the techniques led to a bias that would lead to misreporting of emissions. Uncertainty information on the techniques is not equally characterised, however, this information represents the best current knowledge of these uncertainties in the emissions community and so the comparisons reported here are all made with the best knowledge available.

Keywords: EN ISO 16911, Industrial Emissions Directive (IED), European Pollutant Release and Transfer Register (E-PRTR), flow measurement, Monte-Carlo simulation

(Some figures may appear in colour only in the online journal)

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1. Introduction

In the EU, emissions from industrial processes to the environment are controlled by the Industrial Emissions Directive (IED) (European Parliament 2010), which sets out a series of emission limit values (ELV) for different pollutants along with measurement uncertainty requirements. The IED requires operators from relevant industries to obtain a permit from the local competent authority (e.g. the Environment Agency for England), which will set out the necessary environmental protection methods, along with ELV for the polluting substances, with the permit conditions set based on the best available techniques (clause 12 in (European Parliament 2010)). The ELV is a concentration limit (mg m^{-3}) set in the IED for specific pollution sources.

Process plant operators are required to report their emissions of the pollutants, contributing to national emission inventories and feeding into the European Pollutant Release and Transfer Register, E-PRTR (European Parliament 2006, European Parliament 2020). The IED requires monitoring of concentrations of emissions for comparison against the ELVs, while the E-PRTR requires reporting of the mass emissions. E-PRTR addresses a wider array of pollutants than the IED, but has minimum threshold emission volumes, specified in annex II of the regulation for each industrial activity it covers (which are listed in annex I of the regulation), above which it is necessary to report emissions. E-PRTR allows measurement, calculation and estimation of the emissions, but operators must use appropriate data frequency to determine facility releases. The IED requires large combustion plants (total rated thermal input ≥ 100 MW) to continuously measure emitted concentrations of SO_2 , NO_x and dust, although the competent authority can grant exceptions in certain circumstances (e.g. plants with short operational lifespan).

E-PRTR requires member states to set out penalties for infringements of the regulation, so operators cannot just assume the easiest monitoring option will be sufficient. In practice competent authorities will focus their efforts on the largest plants, so they are the most likely to use direct measurement. If measurements indicate that emissions are very stable, then periodic monitoring is likely to meet the requirements, but otherwise the plant will have to utilise automated measurement systems (AMSs) to continuously monitor emissions. The IED requires measurements of SO_2 , NO_x and dust to be made at least once every six months when continuous monitoring is not required.

Since the reported values for E-PRTR are mass emissions, which are calculated by multiplying the concentration by the flow rate, the flow rate also needs to be measured to similarly high standards as the concentration. Potentially the E-PRTR could therefore be used to assess the impact of the IED on cutting emissions, although only where continuous emission and flow rate monitoring is required.

Supporting the legislation are a series of best available technique reference (BREF) documents for each of the industries covered by the IED. These BREF documents outline the ideal techniques to use for particular applications along with recommended associated emission levels (AEL) when in use (e.g.

LCP (large combustion plant) BREF (Lecomte *et al* 2017); WI (waste incineration) BREF (Neuwahl *et al* 2019)). From the BREF documents best available technique conclusions (BAT conclusions) are derived and published as Commission Implementing Decisions. These are then the legal basis used by local competent authorities to set site specific permit ELVs.

The BREF documents are reviewed and, if necessary, updated on an eight yearly cycle to keep up with developments in monitoring technology. Generally, this will lead to a tightening of AELs (and subsequently the site-specific permit ELVs issued by local competent authorities) over time, helping to reduce potentially dangerous emissions to the environment. One major challenge created by this process relates to the measurement uncertainty. The IED sets uncertainty requirements for measurements as a percentage of the ELV, so when an ELV is lowered the measurement uncertainty requirements become more stringent too. In some areas this is becoming increasingly difficult due to the standardisation process that supports the measurements.

It is worth noting here that the BREF documents have extended the requirements to some pollutants not included in the IED. The BREF documents do not include any uncertainty requirements since this is outlined in the IED. Some species therefore are being regulated without any standardised uncertainty requirements in EU legislation. This oversight risks an inconsistent regulatory approach across the EU as the 28 national regulators are left to independently set their own uncertainty requirements, so harmonisation is unlikely.

National, European and International standards define how the concentration and flow of pollutants should be measured. The European Committee for Standardisation (CEN) provide validated measurement methods that meet the measurement uncertainty requirements in the legislation. Reference methods (RMs) are fully described, can be manual or automatic and will give the accepted reference value of a measurand (BSI 2007). Local competent authorities can then decide which CEN methods are to be specified as standard reference methods (SRMs) for each measurement, as stated in European or national legislation. New measurement techniques introduced in updated BREF documents must demonstrate that they are equivalent to the existing SRM in order to be approved for use as an alternative method (AM). The requirements are set out in EN 14793 (BSI 2017b) and include the maximum expanded uncertainty of the AM being equal or lower than the maximum expanded uncertainty of the SRM at the ELV. EN 14793 assumes that the SRM measures the 'true' value exactly, so even if the new method under test provides a better measurement it still must be close enough to the measurement provided by the existing SRM, potentially limiting step changes in performance.

The standard for stationary source emission volume flow rate in ducts is EN ISO 16911 which is split into two parts, (1) (BSI 2013a) covering the manual RMs and (2) (BSI 2013b) covering AMSs. The AMS is installed at a site to complete the long-term monitoring required by the IED, while the manual RM will be used periodically to produce parallel measurements for calibration purposes. EN ISO 16911-1 can be used for measuring circular or rectangular ducts providing the measurement location meets requirements set out in EN

15259 (BSI 2007a). There are minimum and maximum duct size restrictions based on the practical considerations of the measurement equipment.

The quality assurance regime described in EN ISO 16911-2 is based on the standard used for quality assurance of automated measuring systems, EN 14181 (BSI 2014). The quality assurance scheme is defined in order to minimise uncertainty to satisfy the requirements of the IED. EN 15267-3:2007 (BSI 2007b) requires the total uncertainty of an AMS being certified to be at least 25% below the maximum permissible uncertainty to provide ‘sufficient margin for the uncertainty... to pass QAL2 and QAL3 of EN 14181 successfully’. Since operators do not need to provide an uncertainty on their reported annual mass emissions, it is assumed that demonstrating that EN 14181 and EN ISO 16911 have been followed with a suitably certified AMS shows they are also meeting the uncertainty limits in the IED.

Ducts need to be characterised using a RM to understand the flow profile and to select a representative point for deploying the RM when making parallel measurements against an AMS. Point measurements are made of the flow velocity across the duct to determine the flow profile, along with mean and volume flow rates in the duct. A representative point is then chosen if possible based on the flow profile, otherwise grid measurements are required for the parallel measurement with the AMS. Point locations are chosen based on the size and shape of the duct, with one or more transects being used in round ducts and gridded sampling points for rectangular ducts on a cross-section. The average velocity for the cross section is calculated from the point measurements and is multiplied by the cross-sectional area to determine the mass flow rate per unit time.

EN ISO 16911-1 outlines how to use differential pressure devices (L- and S-type Pitot tubes) and vane anemometers as RMs for making the point measurements. The standard also outlines three alternative methods based on tracer dilution measurements, tracer transit time measurements or calculations from the energy consumption of the combustion process to determine the volume flow rate. Beyond these valid techniques, any alternative approach (e.g. hot wire anemometer) would need to demonstrate equivalence in accordance with EN 14793 and be accepted by the local competent authority.

Pitot tubes measure flow velocity at a point in the duct using the principle of differential pressure measurement. There are several variants that vary in their design and implementation (Dimopoulos *et al* 2017). The L-type Pitot tube has one pressure tap open directly into the flow with a second static pressure tap perpendicular to the flow. From the pressure differential between the two pressure measurements it is possible to interpret the measured flow at the point in the duct. The S-type Pitot tube has the two pressure taps back to back so one is directly in the flow and the other gives a static pressure level. The 3D Pitot tube has a shaped head with multiple pressure taps in different directions on it. By using differential pressures between multiple pairs of taps it is possible to calculate the yaw and pitch of the flow direction relative to the Pitot tube, along with the overall flow rate.

Vane anemometers use the force of the flow in the duct to rotate the cups and the number of rotations per unit time can be converted into a flow rate based on the calibration. Particulate matter can settle on the anemometer which would alter the rate of rotation under a given force, so these devices should not be used with dusty processes.

Tracer dilution involves injecting a known, traceable flow rate of a calibrated tracer gas into the duct, then measuring the concentration at a point downstream where mixing of the tracer has been completed (Graham 2004). The level of dilution of the trace gas indicates the flow rate, with high dilution indicating faster flow rates and vice-versa. The type of tracer gas is an important consideration as if there is any change in the background concentration the measurement will be inaccurate.

Transit time tracer measurement involves short sharp pulses of tracer gas being injected into the duct. Downstream from the injection point and where the pulse has mixed over the cross-section, two measurement points are placed a known distance apart along a straight section of duct. From the time difference for detection of the pulse and the volume of the duct between the measurement points you can calculate the volume flow rate for the section of duct.

Volume flow rate from plant thermal input requires measurement of the amount and quality of the fuel going into the combustion chamber, along with the thermal energy input rate and the volume of the flue. Calculation methods are defined in EN 12952-15 (BSI 2003). Oxygen concentration measured using EN 14789 (BSI 2017a) can be used to determine and correct for the volume of excess air in the duct to give the actual volume flow rate.

Hotwire anemometers are not directly covered in EN ISO 16911-1, but are commonly used for flow testing applications in other fields and are mentioned as being within the scope for a method implementation document (MID) for EN ISO 16911-1 produced by the Environment Agency for England (Environment Agency 2017). Note, the authors could not find any published evidence of hotwire anemometers going through testing as an alternative method.

Hotwire anemometers work by monitoring a wire exposed to the flow, which either maintains a constant current so the wire temperature will change with flow rate, or it maintains a constant temperature by varying the current which is then a proxy for the flow rate. If flow rate is faster the heat in the wire will be dissipated quicker. Consideration must be made for the relative wire and stack gas temperatures as these will have a significant impact on any potential calibration function for the device. Calibration functions are non-linear, so sensitivity will vary dependant on flow rates.

With six different potential RMs, three of which were characterised for EN ISO 16911-1, there is plenty of scope for performance differences which might affect reported emissions when used for calibrating AMS. Assessment of these differences is challenging, however, since the characterisation of the different methods is not equally robust.

The quantity and quality of uncertainty information provided in the standard is variable. The most comprehensive uncertainty information is for the L- and S-type Pitot tubes. Also, as these are essentially variants of the same technique

(differential pressure) and uncertainty values are provided for the same set of performance characteristics, then comparison between these two techniques is likely to be the most reliable. However, there are still some imperfections in this comprehensive set of uncertainty information, namely, the yaw error is the same for both types of Pitot tube. This is an issue as the S-type due to its design enables some correction of yaw (as the tube can be turned until the direction of flow is found). This is not accounted for in the results reported here and the yaw error is taken to be the same for both types of Pitot tube. However, this has negligible impact on the results because testers should be trying to minimise both pitch and yaw misalignment regardless of the type of Pitot being used. With respect to the vane anemometer and hot wire techniques the uncertainty information is less comprehensive than for the Pitot tubes. However, this information none-the-less represents the best current knowledge of these uncertainties in the emissions community (Smith *et al* 2017) and so the comparisons reported here are all made with the best knowledge available.

The limitation of modelling the emission uncertainty is only in the quality of the basis and inputs for the model. Poor or incomplete information in the standard will affect the quality of the model. As mentioned above there is a potential issue with the L-type Pitot yaw alignment uncertainty, which the model cannot account for. As a result the model can only provide a comparison based on the information in the standard which represents the best knowledge currently available. Similarly how each technique is represented in the model will depend on the available information on the techniques, so for the hot-wire anemometer which has not been used for monitoring stacks the leading knowledge is still likely to be less detailed and accurate than for the methods validated in the standard.

The model used here goes beyond the flow uncertainty, covering both concentration and flow uncertainties for AMS measurements and the associated parallel reference measurements, which all contribute to the calculation of reported mass emissions. This allows the model to put the flow uncertainties in the practical context in which the techniques are used, providing an indication of the reported mass emission uncertainty derived from the flow monitoring techniques. This will ensure that efforts can be targeted to improve emission quantification and make reporting more reliable, helping operators and regulators to maintain safe limits.

A Monte-Carlo simulation (MCS) model was initially developed to focus on concentration measurement uncertainty using EN 14181 (Smith *et al* 2019, Smith 2018), demonstrating that in most circumstances following the standard would allow the operator to meet the IED monitoring uncertainty requirements. Smith *et al* did find that uncertainty on the concentration RM had greater impact on the overall mass emissions than uncertainty on the AMS, since a poor calibration would leave a bias on all AMS measurements using that calibration function.

The model has now been extended to include implementations for a number of alternative flow RMs operating under EN ISO 16911. Previous work by Dimopoulos *et al* (Dimopoulos *et al* 2017) described the improvements in EN ISO 16911

compared to the earlier ISO 10780 standard (ISO 1994). These include more reference techniques, corrections for cyclonic flow effects, assessment of alignment errors and wall effect correction factors. Laboratory and field testing was carried out to validate these additions, however, this did not include testing on a stack with cyclonic flow. Workamp *et al* (Workamp *et al* 2020) have subsequently investigated the effects of swirl in narrow ducts using test bench and computational fluid dynamic modelling experiments, demonstrating that it can contribute errors up to 15% in certain circumstances, although this can be reduced by measuring at multiple points on the sampling plane.

This paper builds upon the results from Dimopoulos *et al* (Dimopoulos *et al* 2017) and Smith *et al* (Smith *et al* 2019), investigating the effect of different RMs being used for the measurement of flow for calculating mass emissions. As the RM sets the calibration for the AMS, any error in it will present as a bias in all measurements until the next calibration. EN 14181 assumes that the RM is perfect, so will not create any systematic errors. The model will be used to test the effects on annual mass emission uncertainty of using L-type Pitot, S-type Pitot, vane anemometer or hotwire anemometer as the RM for flow AMS calibration. This will compare the effect of using these four techniques on the uncertainty of annual mass emissions, using the best available information, indicating if certain methods are better or worse when considering which to use for AMS calibrations.

2. Method

In order to understand how the uncertainty on a particular method affects the uncertainty in the reported annual mass emissions, a model has been implemented to simulate the whole process (Smith *et al* 2019). This uses MCS techniques to propagate the uncertainty from all sources that contribute to the reported annual mass emissions.

The MCS can be set up to represent either one instrument making repeat measurements or as a population of different instruments sampling the same emission stream. For this work we are focussing on the case of a population of different instruments (i.e. each repeat will have slightly different characteristics for the instrument within the stated uncertainty ranges). The model runs many times and, on each model repeat, the probability distribution function for each uncertainty source within the process is sampled randomly. This produces a set of results that represent a population of instruments measuring the same emissions. By looking at all of these model repeats together there will be a range of results which represent the potential measurement outcomes, so the standard deviation of the model output is the overall uncertainty of the reported annual mass emissions.

Implementation in the model was largely based on the content in EN ISO 16911, with some additions where necessary to fully account for measurement uncertainties. Appendix A provides a full list of the uncertainty sources implemented in the model for each RM (either SRM or AM), while appendix B includes test settings that are constant across all runs.

Where there are uncertainty limits listed in EN ISO 16911 they have been used as a limit for the high uncertainty scenarios. Many of the typical uncertainty values used come directly from the validation data sets in the appendices of EN ISO 16911 as detailed below. The low uncertainty levels have been set by expert judgement based on the typical and high uncertainty levels and influenced by what is realistically achievable with current technology.

Appendix A of EN ISO 16911-1 covers differential pressure based measurement techniques, i.e. Pitot tubes. These share many of the same measurement uncertainties relating to manometers (e.g. uncertainty on a single reading due to repeatability/temperature/atmospheric pressure/calibration/etc), however due to their different geometry in the flow some uncertainties are different, particularly related to the pitch and yaw uncertainties. On that point the uncertainties in appendix A for Pitot yaw error is the error per degree of yaw off-set, so this is the same for both L- and S-type, but you would expect the S-type to exhibit lower yaw offsets due to the yaw-correction procedure.

The L-type Pitot gives no indication of potential misalignment with the axial flow direction so is more prone to pitch and yaw related uncertainty. With the main pressure tap directly facing the axial flow direction there is also potential for fouling of the Pitot if dust or other debris is present in the gas flow. To account for this the model includes uncertainty variables for these sources.

The S-type Pitot can be rotated within the flow to find the direction of axial flow, indicated when the pressure difference is greatest between the two pressure taps. This can minimise potential uncertainty from this source compared with the L-type Pitot. The S-type is also prone to fouling of the active pressure tap, but since the static pressure tap is sheltered from the flow and therefore fouling, there is a potential indicator which could improve detection when this occurs, hence reducing the impact of this factor.

3D-Pitot tubes are also included in EN ISO 16911-1. Since they have multiple pairs of inlets both yaw and pitch misalignment can be corrected for. In the model pitch and yaw errors are both included, but only yaw uncertainty can be assessed for L- and S-type Pitot tubes. Similar levels of pitch and yaw error are assumed, but with no correction for pitch in the L- and S-type Pitot representations.

Appendix B of EN ISO 16911-1 outlines the use of vane anemometers for measuring flow velocity in ducts. The uncertainty related to the process described in the appendix is somewhat limited as, for example, it does not take into account the uncertainty on the calibration of the anemometer. The model adds an uncertainty based on the calibration quality (e.g. calibration uncertainty of 1% of measured flow), but potentially more could be considered when assessing all potential uncertainty sources relating to this method. The appendix includes performance requirements for vane anemometers, one of which is minimum velocity since they require a certain amount of flow before the vanes will start to turn. The model needs to cope with velocities below 0.5 m s^{-1} , so when these occur it assumes zero flow. The model will therefore underestimate annual mass emissions in cases where emissions occur at

very low flow rates when using vane anemometers, but this is an accurate representation of true vane anemometer behaviour.

For hotwire anemometers the standard does not include uncertainty examples, so a number of other sources were used when formulating model equations and variables (Rezaeiravesh *et al* 2018, Laurantzon *et al* 2012, Kurtuluş 2009). Turbulence in the flow will also alter the mixing rates so the model uses a slightly modified equation for flow with low Reynolds number. Heat transfer from the wire to the duct walls when measuring close to them (Ikeya *et al* 2017) has not been included in the model, although this could be an issue for facilities with narrow ducts leading to higher uncertainty than demonstrated in the model. Moisture will significantly change the thermodynamics of the wire, so for a stack with varying humidity levels (e.g. waste incineration processes) the calibration may not be valid for all moisture conditions. The model assumes that flow temperature and humidity remain stable around the levels occurring during calibration, but in reality this is unlikely to be the case, so the model is likely to underestimate the uncertainty resulting from using a hotwire anemometer. Since the authors were unable to identify a hotwire anemometer that has been approved for use in stack monitoring the uncertainty values detailed in appendix A are based on expert judgement rather than a specific instrument.

Each run of the model was carried out with fixed flow rates, so repeated runs were made for low, medium and high process flow rates for each modelled RM (table 1). This provides an indication of the performance of the RM techniques when operating under widely different flow regimes. Additional tests were run with varying flow rates fitted to a sine wave to represent natural changes in flow rates over longer periods (e.g. daily, weekly and annual cycles).

For all runs the flow AMS uncertainties were set to zero, along with the concentration measurement uncertainties. This isolates the uncertainty from the different flow RMs and the propagation into the reported annual mass emissions, demonstrating the impact of the uncertainty arising from each flow RM on the final result.

The uncertainties used within the model for each RM are based on typical expected values for one set of tests. Further tests have been run based on high (i.e. close to limit values) and low uncertainty values to investigate the range of effects that will fall within the method uncertainty requirements in EN16911-1. Appendix A lists the variables for each RM along with the typical, low and high uncertainties used. Appendix B contains a table of shared test characteristics for all model runs.

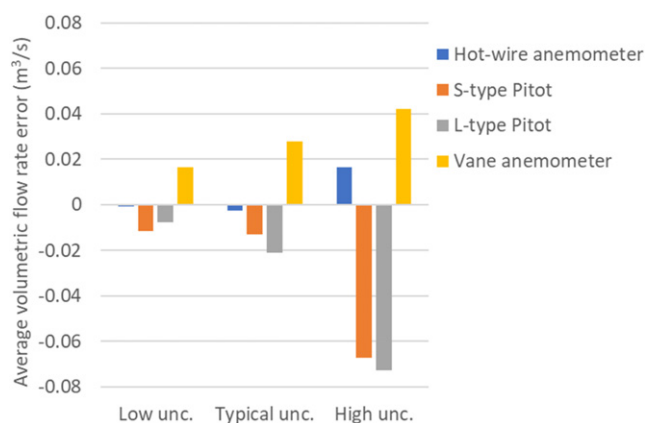
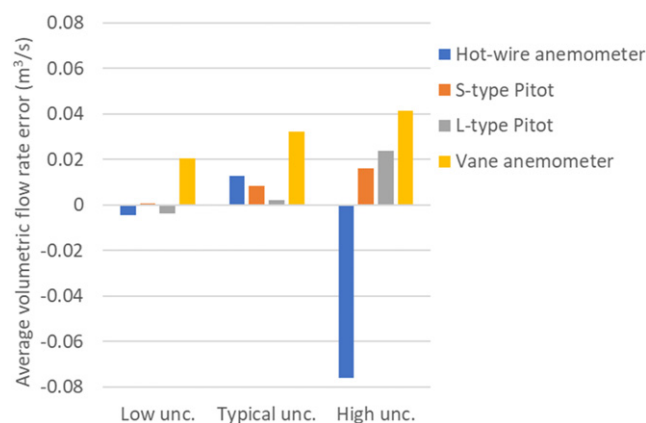
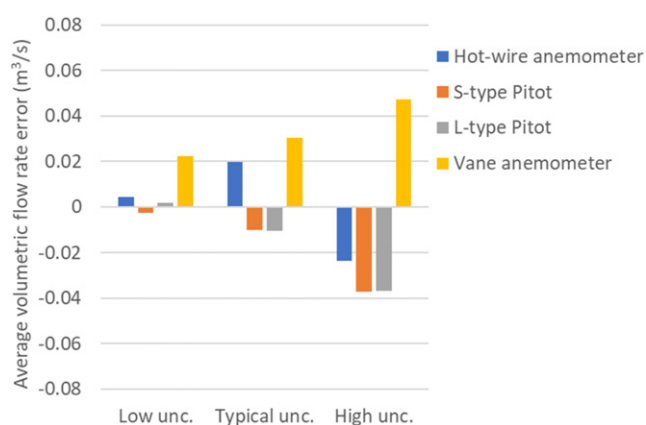
3. Results and discussion

When looking at model output it is important to be confident that results are representative of real situations and not just an artefact of how the model is written. The results were investigated to demonstrate that the model was not introducing its own artefacts in the results.

One potential issue would be related to the seeding of the random number generators (RNG) used in the model. In R the default seed for the RNG is based partly on the time, so if multiple calls are made to seed different RNG in a very short time

Table 1. Flow rates during test runs given as measured rate/ m s^{-1} and volumetric flow rate/ $\text{m}^3 \text{s}^{-1}$.

Test description	Average measured flow rate/ m s^{-1}	Average volumetric flow rate/ $\text{m}^3 \text{s}^{-1}$
Low flow (constant)	5	10
Medium flow (constant)	20	40
High flow (constant)	40	80
Daily flow cycle (variable)	20 (range 10–30)	40 (range 20–60)
Monthly flow cycle (variable)	20 (range 10–30)	40 (range 20–60)
Yearly flow cycle (variable)	20 (range 10–30)	40 (range 20–60)

**Figure 1.** Average volumetric flow rate error from model runs for each technique, grouped by the RM uncertainty settings. These had constant low volumetric flow rates of $10 \text{ m}^3 \text{s}^{-1}$.**Figure 3.** Average volumetric flow rate error from model runs for each technique, grouped by the RM uncertainty settings. These had constant high volumetric flow rates of $80 \text{ m}^3 \text{s}^{-1}$.**Figure 2.** Average volumetric flow rate error from model runs for each technique, grouped by the RM uncertainty settings. These runs had constant medium volumetric flow rates of $40 \text{ m}^3 \text{s}^{-1}$.

(e.g. repeated seeding in a loop), you could end up with the same seed being used repeatedly, causing separate repeats to use the same sets of random numbers, leading to a repeated bias source. Short runs with ~ 50 repeats did indicate this could potentially be a slight issue. The results presented here are from model runs with 10 000 repeats and a runtime of over 36 h though, so while one or two instances of repeated seeds could occur, it is unlikely to have a significant impact on the overall outputs unless it is systematically occurring with specific uncertainty sources. The authors can find no evidence of

this being the case so conclude that there are no issues with the way this aspect of the model is coded.

The way some errors are implemented in the model, e.g. limit of detection, leads to any value below a threshold being treated as a set value, which could result in a bias that might not be representative of the real measurement. However, the majority of errors are not implemented like this and any effect would be lower than the limit of detection that is an accepted uncertainty anyway. As such this is unlikely to be a significant source of bias in the model results.

The sample loss rate, which is known to exist, but in the real world is controlled by implementing leak checks that will limit the scale of any leaks in the sampling system, could cause negative bias if set inappropriately. EN 14181 and EN ISO 16911 do not set threshold levels for passing leak checks, they just require that they are carried out. CEN/TR 17078 (CEN/TC 264 2017), which provides guidance on the use of EN ISO 16911-1, specifies that the differential pressure should remain stable to within $\pm 2.5 \text{ mm H}_2\text{O}$ for at least 15 s at high pressure to demonstrate no leaks in the system. In appendix B of that technical report it specifies a velocity pressure of $76 \text{ mm H}_2\text{O}$ for the test, which would represent a threshold of $\sim 3.3\%$. Based on this a 2% threshold level was used within the model as this is within acceptable limits and so is unlikely to be producing a false model bias.

These tests demonstrate that the model was performing as expected and was ready for longer runs to generate the results with the different RMs.

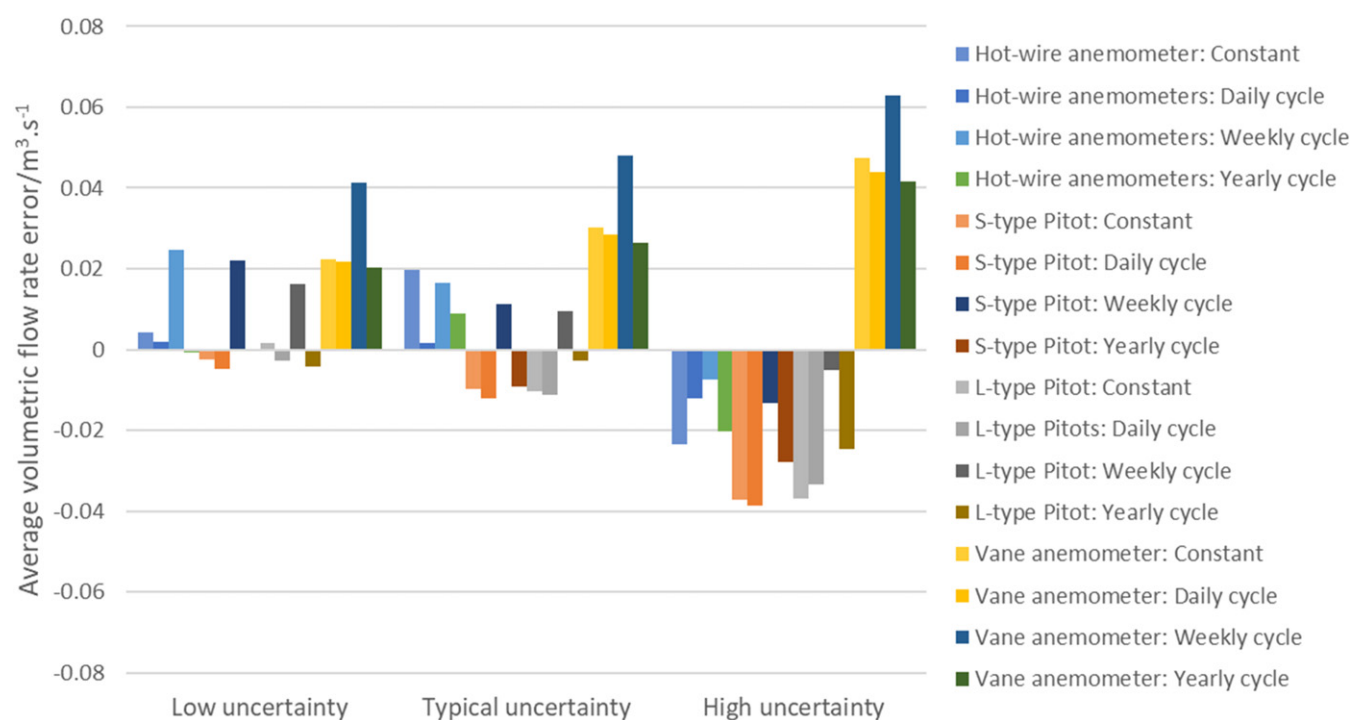


Figure 4. Average volumetric flow rate error from model runs with average flow rates of 40 m³ s⁻¹ through a constant flow regime or flow varying between 20–60 m³ s⁻¹ following a sine wave with daily, weekly or annual wavelength.

As mentioned above the uncertainties of the various techniques considered have not all be characterised to an equal extent. Consequently, there is some variance in the quantity and quality of the information. However, this, none-the-less, represents the best uncertainty knowledge currently available within the emissions community and therefore comparison is appropriate on this basis. Clearly, as new uncertainty information becomes available in the future it will be important to repeat this work and improve our understanding of how these techniques compare in the stack flow measurement environment.

In general, the average absolute error in volumetric flow rate is small (figures 1–3 and supplementary figures C1–C3), however, these errors cannot be ignored as they are systematic creating a bias on each measurement, which will become significant once combined into the reported annual mass emissions. To illustrate this, a bias of just 0.02 m³ s⁻¹ would contribute to an error of 350.4 m³ on the annual emission volume. It should also be noted that these model runs assume a perfect AMS so all the error is coming from the calibration and the expected total uncertainty on the flow measurements in normal operation would be higher than is seen here.

As expected, the errors on the high flow model runs for most instruments are highest. This is because many of the individual uncertainties are stated as a percentage of the measured variable, so at higher flows the total uncertainty will be higher if these forms of error are present. In contrast the low flow runs will have far smaller contributions from those sources, but fixed uncertainties, e.g. relating to limit of detection, will maintain a significant underlying error that can lead the low flow runs to have higher errors than other scenarios.

Different RM instruments lead to variable calibrations affecting the measured volumetric flow rates. Figure 4 illustrates the varied effects of both the different methods and the uncertainty scenarios.

The hot wire anemometer performance varied, staying below ± 0.04 m³ s⁻¹, with a positive skew at low and typical uncertainties, but negative errors at high uncertainty levels. In addition to this the model does not include the effect of variation in humidity between calibration and measurement, something that would significantly influence the performance of this method.

The L-type Pitot method had the best performance for the low uncertainty regime and limited increases in error for the higher uncertainty scenarios. The S-type Pitot varied very little between the low and typical uncertainty scenarios, although the error was higher for the high uncertainty test, but for all three scenarios it produced errors $< \pm 0.04$ m³ s⁻¹, although it did consistently under measure the true flow.

The vane anemometer produced the highest measurement errors of the included RM tested here. All of the scenarios for the vane anemometer produced positive errors, a bias which would have led to higher measured flow and annual mass emissions.

Figure 5 summarises the annual mass emissions with error bars ($k = 2$) based on the standard deviation of the Monte-Carlo model output. For many of the scenarios these do not intersect with the marked true annual mass emission total. In particular the vane anemometer has very small error bars due to the limited uncertainty assessment included in EN ISO 16911-1 upon which the model uncertainties were based. This

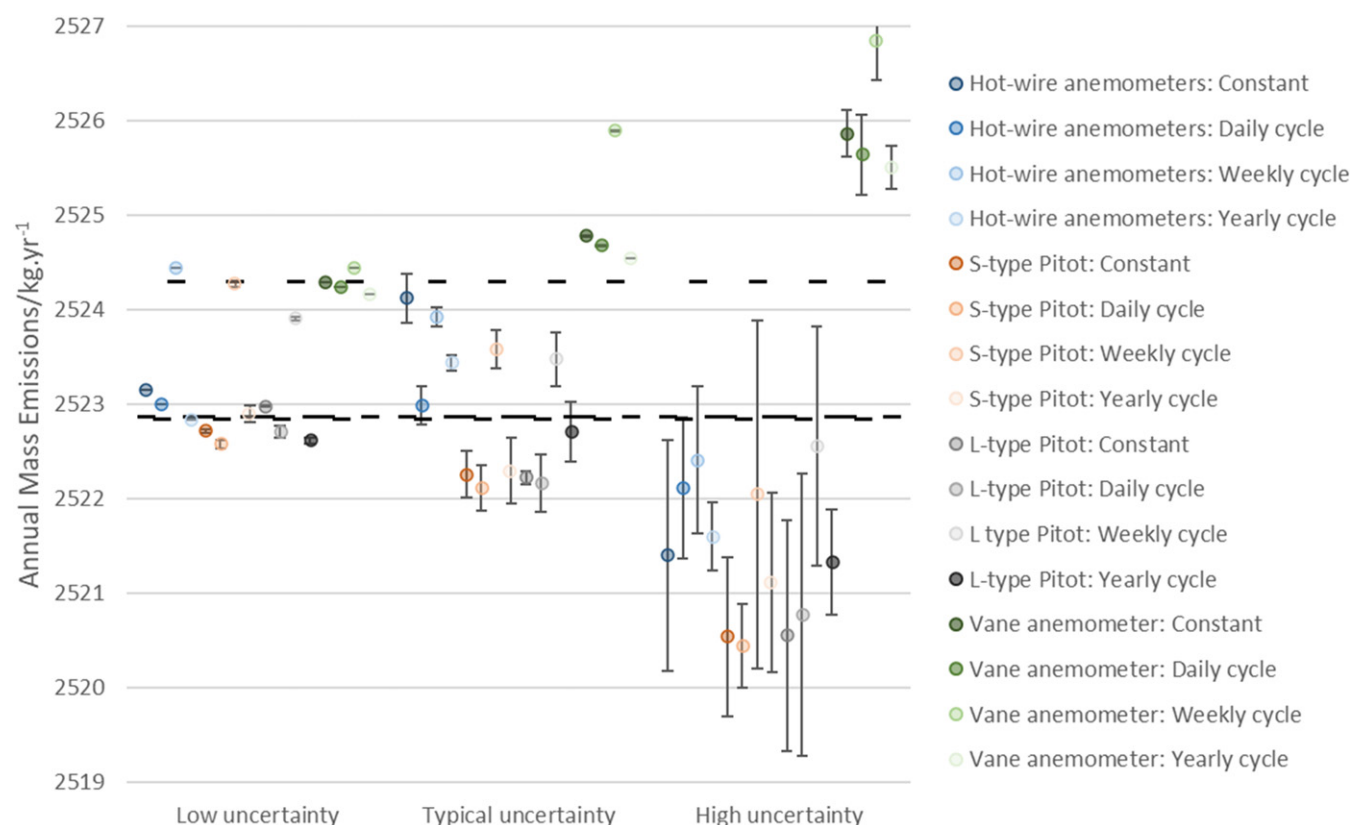


Figure 5. Simulated annual mass emissions when calibrating with different reference techniques and under typical, low and high uncertainty regimes with 95% confidence interval error bars. Average flow rates of $40 \text{ m}^3 \text{ s}^{-1}$ through a constant flow regime or flow varying between $20\text{--}60 \text{ m}^3 \text{ s}^{-1}$ following a sine wave with daily, weekly or annual wavelength. The bold dashed lines represent the true expected annual mass emissions, with the weekly flow cycle annual mass emission runs being higher due to incomplete weeks causing a slightly higher average flow rate.

demonstrates that the uncertainty assessment is insufficient since none of the error bars intersect the true values.

The uncertainty in the flow RM will produce errors in the flow AMS calibration. This is most likely to mainly be made up of an offset in the flow measurements. When this is propagated through to the annual mass emissions by the model, this offset will not necessarily affect the spread of model outputs, so the error bars in figure 5 will not cover the full extent of the error displayed in the annual mass emissions.

4. Discussion

The results demonstrate an apparent negative bias in all the RMs tested except the vane anemometer, which shows a positive bias. Model related causes of this were eliminated from consideration indicating that this is a real result. Consistent underestimation of flow would lead to systematic under-reporting of annual mass emissions so is something that should be investigated further.

The differential pressure based systems (L- and S-type Pitot tubes) performed consistently over all uncertainty and flow scenarios. Both forms of Pitot did produce some negative bias in the higher uncertainty scenarios (although not at higher flow rates where there was positive bias (figure 3)), but otherwise were some of the best performing methods. The Pitot tube

RMs alignment errors would lead to lower differential pressures during calibration leading to the negative offsets. Further tests isolating the contribution from pitch and yaw alignment issues could resolve whether this is the cause of the bias in these cases.

The vane anemometer produced consistent results with limited sensitivity to changes in flow regime and a steady increase in errors with rising uncertainty. This could be seen to suggest that it is a reliable method for calibration, but the model results demonstrate accuracy issues and insufficient variance to account for the error. This could be due to some combination of insufficient detail in the uncertainty assessment in EN ISO 16911-1 and the resulting implementation of the method in the model.

The vane anemometer modelled for these tests has a limit of detection of 0.5 m s^{-1} . When the flow rate is at or below this level the model counts it as reading zero which would introduce a negative bias. As part of the calibration when data is clustered, zero and span measurements are made to extend the valid calibration range. The influence of a poor zero point could lead to a calibration function with a bias at some flow rates.

The vane anemometer also does not have any uncertainty contribution from misalignment with the axial flow. Misalignment is likely to result in measurement errors of up to 10%

(Pedersen *et al* 2006). Misalignment is most likely to occur where there is high swirl within the measurement section. This source of uncertainty is omitted in EN ISO 16911-1 so was not implemented within the model, so these results provide a conservative estimate of vane anemometer error in high swirl measurement locations.

The hot-wire anemometer results demonstrate a more even distribution of positive and negative errors relative to the reference value. Hot wire anemometers are widely used for flow measurement in engineering, but the challenges of emission measurement, particularly in relation to the effects of frequent and rapid changes in humidity of the stack gas stream, would suggest why it is not currently a commonly used technique in this field. The model results for the technique show comparatively high uncertainties, which do a better job of characterising the error than other RMs. However, due to the limited uncertainty information available since it was not characterised within EN ISO 16911-1, firm conclusions on the suitability of hotwire anemometer for this application cannot be made. Prior to any use as a RM it would have to go through the EN 14793 equivalence testing to demonstrate it is equivalent, which could provide improved uncertainty characterisation of the technique in order to repeat this analysis of performance against the alternative reference techniques. The uncertainties for the various techniques are not equally robustly characterised, with variance in the quality and quantity of information, although this does represent the best uncertainty knowledge currently available within the emissions community. As any new information is developed in future, it will be important to repeat this work to improve our understanding of how these techniques really compare in the stack flow measurement environment.

5. Conclusions

All of the modelled techniques (except the vane anemometer) have demonstrated a tendency to calibrate in a negative bias for flow measurements, something which will result in under reporting of pollutants when calculating the mass emissions. When the methods achieve the lowest uncertainty levels tested the Pitot tubes proved to be the best RM to use, capable of providing calibrations with minimal bias so that accurate mass emissions could be calculated.

Minimising uncertainty should be a key concern for any measurement and these tests have demonstrated the impact of ensuring that methods are implemented in a way to reduce uncertainty. Even though the high uncertainty variables met the requirements, these runs were affected by systematic bias, the impact of which is compounded when propagating over longer annual reporting periods. The hot wire anemometer displayed positive bias at low and medium uncertainties, but negative bias at high uncertainty levels over all the tests. This inconsistency could indicate a lack of suitability for this method when measuring in hot and wet stack environments, requiring further investigation. Strong conclusions about the hotwire anemometer performance cannot be made since there is no uncertainty

information available for their use in this application, so model parameters had to be based on expert judgement.

Both forms of Pitot tube included in the tests showed some negative bias, but this was reversed at very high flow rates leading to a slight positive bias instead when modelled flows were $80 \text{ m}^3 \text{ s}^{-1}$. This was not seen in the tests where the flow rate cycled over any period, with the Pitot tube results indicating a negative bias. The vane anemometer produced a positive bias in all flow scenarios tested, which would lead to erroneously high emission rates. The hot-wire anemometer did not display any significant variation between the different flow scenarios tested.

EN ISO 16911-1 does describe further methods (3D-Pitot, time-of-flight tracer, dilution tracer and heat accountancy calculation) for calculating mass flow rates so it would be interesting to expand the model to include these techniques, providing a complete picture of the effect of choosing different RMs for flow AMS calibration. Improved characterisation of uncertainty of the different available techniques will be key for a more conclusive comparison of their relative performances. However, based on the current best available characterisations, all flow calibration techniques have their limitations and further development is required to improve the metrology sufficiently to close the gap and produce methods which can consistently and reliably provide accurate calibrations free from bias, as is assumed in the measurement standards for emission concentration and flow measurements (BSI 2014, BSI 2013).

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Appendix A. Reference method uncertainty variables and test settings

See tables A1–A4.

Appendix B. Shared test settings for all model runs

See table B1.

Appendix C. Supplementary figures

See figures C1–C3.

Appendix D. Probability density function information

See table D1.

Table A1. L-type Pitot tubes.

Variable	Description	Low setting	Typical setting	High setting
Calibration error	Error on the Pitot calibration	0.2%	0.28%	0.8%
Repeatability	Repeatability of measurements	0.3%	0.5%	0.8%
Pitch error	Error from pitch misalignment	0.5%	1%	2%
Yaw error	Error from yaw misalignment	0.5%	1%	2%
Drift	Drift in the manometer	0.05%	0.1%	0.5%
Linearity	Error from non-linearity in calibration function	0.04%	0.06%	1.5%
Fouling	Error from debris blocking up the Pitot inlets	0.5%	1%	2%
Calibration function reproducibility	Variation in calibration function of the Pitot between model repeats	0.25%	0.5%	1%
Atmospheric pressure uncertainty	Uncertainty in the measurement of the atmospheric pressure during the measurement	120 mBar	170 mBar	300 mBar
Temperature uncertainty	Uncertainty in the flow temperature measurement	1 K	1.5 K	4 K
O ₂ uncertainty	Uncertainty in the flow O ₂ content	2% (relative)	3% (relative)	5% (relative)
CO ₂ uncertainty	Uncertainty in the flow CO ₂ content	2% (relative)	3% (relative)	5% (relative)
H ₂ O uncertainty	Uncertainty in the flow H ₂ O content	7.5% (relative)	10% (relative)	15% (relative)

Table A2. S-type Pitot tubes.

Variable	Description	Low setting	Typical setting	High setting
Calibration error	Error on the Pitot calibration	0.2%	0.28%	0.8%
Repeatability	Repeatability of measurements	0.3%	0.5%	0.8%
Pitch error	Error from pitch misalignment	0.5%	1%	2%
Yaw error	Error from yaw misalignment	0.5%	1%	2%
Drift	Drift in the manometer	0.05%	0.1%	0.5%
Linearity	Error from non-linearity in calibration function	0.04%	0.06%	1.5%
Fouling	Error from debris blocking up the Pitot inlets	0.5%	1%	2%
Calibration function reproducibility	Variation in calibration function of the Pitot between model repeats	0.25%	0.5%	1%
Atmospheric pressure uncertainty	Uncertainty in the measurement of the atmospheric pressure during the measurement	120 mBar	170 mBar	300 mBar
Temperature uncertainty	Uncertainty in the flow temperature measurement	1 K	1.5 K	4 K
O ₂ uncertainty	Uncertainty in the flow O ₂ content	2% (relative)	3% (relative)	5% (relative)
CO ₂ uncertainty	Uncertainty in the flow CO ₂ content	2% (relative)	3% (relative)	5% (relative)
H ₂ O uncertainty	Uncertainty in the flow H ₂ O content	7.5% (relative)	10% (relative)	15% (relative)

Table A3. Vane anemometers.

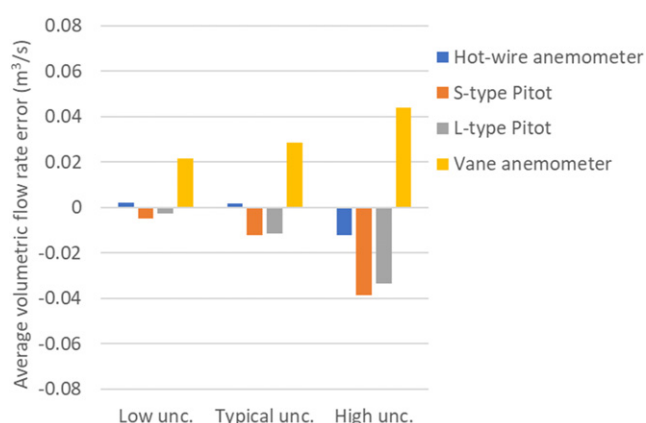
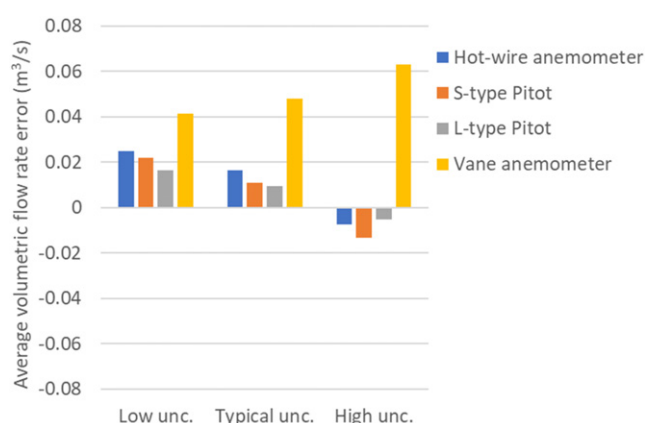
Variable	Description	Low setting	Typical setting	High setting
$V_{\min}$	Minimum measurable flow	0.2 m s ⁻¹	0.3 m s ⁻¹	0.5 m s ⁻¹
$V_{\max}$	Maximum measurable flow	50 m s ⁻¹	50 m s ⁻¹	50 m s ⁻¹
$F_{\max}$	Maximum measurable rotation frequency	3000 Hz	3000 Hz	3000 Hz
e_p	Measurement reproducibility	0.01	0.015	0.02
Lack of fit	Calibration uncertainty	1%	1.5%	3%
$V_{\min}$ uncertainty	Minimum flow rate uncertainty	0.01 m s ⁻¹	0.05 m s ⁻¹	0.1 m s ⁻¹
$V_{\max}$ uncertainty	Maximum flow rate uncertainty	0.1 m s ⁻¹	0.2 m s ⁻¹	0.5 m s ⁻¹
$F_{\max}$ uncertainty	Maximum frequency uncertainty	0.5%	1%	2%

Table A4. Hot-wire anemometers.

Variable	Description	Low setting	Typical setting	High setting
Wire temperature uncertainty	Uncertainty of measurement of the wire temperature	0.25 K	0.5 K	2 K
Voltage uncertainty	Uncertainty of measurement of the voltage through the wire	0.25%	0.5%	1%
Calibration offset uncertainty	Uncertainty in the offset of the calibration	0.25%	0.5%	1%
Calibration slope uncertainty	Uncertainty in the slope of the calibration	0.25%	0.5%	1%
Flow temperature uncertainty	Uncertainty of measurement of the flow temperature	0.25 K	0.5 K	2 K

Table B1. Shared test settings.

10 000 MCS repeats
2 mg m ⁻³ concentration
15 QAL2 points
2% loss rate
Round duct with 2 m ² cross sectional area
Zero cross sectional area uncertainty
Homogenous concentration at measurement location
500 Reynolds number flow
30 min average measurements for both concentration and flow
Zero error from offset concentration and flow measurements
Timeless quality tests (i.e. no data interruption when running QAL2/QAL3/AST)
Zero flow AMS error
Zero concentration error (SRM and AMS)

**Figure C1.** Average volumetric flow rate errors for runs with each technique. Medium average flow rate of 20 m s⁻¹, but following a daily sinusoidal distribution ranging between 10–30 m s⁻¹.**Figure C2.** Average volumetric flow rate errors for runs with each technique. Medium average flow rate of 20 m s⁻¹, but following a weekly sinusoidal distribution ranging between 10–30 m s⁻¹.

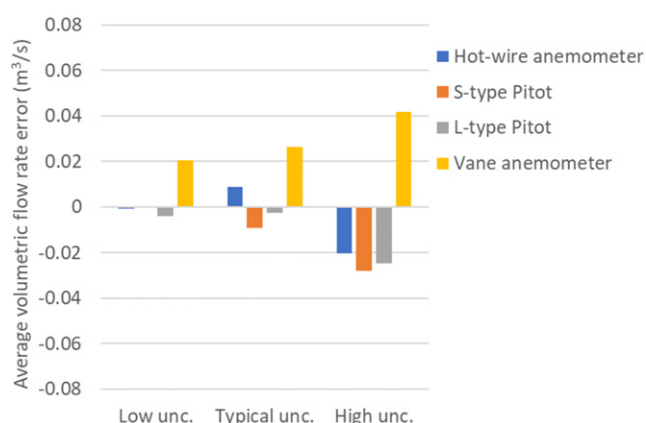


Figure C3. Average volumetric flow rate errors for runs with each technique. Medium average flow rate of 20 m s^{-1} , but following a yearly sinusoidal distribution ranging between $10\text{--}30 \text{ m s}^{-1}$.

Table D1. PDF types.

Parameter	PDF type
Calibration error	Normal
Repeatability	Normal
Pitch error	Normal
Yaw error	Normal
Manometer drift	Normal
Manometer linearity	Normal
Fouling	Normal
Calibration function reproducibility	Normal
Atmospheric pressure uncertainty	Normal
Temperature uncertainty	Normal
O ₂ uncertainty	Normal
CO ₂ uncertainty	Normal
H ₂ O uncertainty	Normal
Lack of fit	Normal
V _{min} uncertainty	Normal
V _{max} uncertainty	Normal
F _{max} uncertainty	Normal
Wire temperature uncertainty	Normal
Voltage uncertainty	Normal
Calibration offset uncertainty	Normal
Calibration slope uncertainty	Normal
Flow temperature uncertainty	Normal
Loss rate	Normal
Cross-sectional area uncertainty	Normal
Flow AMS detection limit	Uniform
Flow AMS repeatability	Normal
Flow AMS linearity	Normal

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