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Uncertainty estimates of tracer gas dilution flow measurements in large-scale exhaust ducts

Rodney A. Bryant

National Institute of Standards and Technology, 100 Bureau Drive, MS 8662, Gaithersburg, MD 20899, United States

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ABSTRACT

Accurate measurements of volume or mass flow in large conduits can be difficult to achieve due to non-ideal flow characteristics such as asymmetry of the velocity profile and off-axis flow components due to swirl. The tracer gas dilution method is independent of these and other non-ideal flow characteristics, but relies on the conservation and uniform mixing of the tracer. This study demonstrates the application of the tracer gas dilution method to measure the volume flow in a large-scale exhaust duct used for flue gas venting. The estimated measurement uncertainty was less than ± 3.5% and considered contributions from instrumentation, degree of mixing, and repeatability of the method. This level of uncertainty demonstrates that the method can be applied as an independent comparison or quality check for other flow measurement methods in large exhaust ducts or flow conduits.

1. Introduction

Many methods exist to measure flow in ducts. Examples include pitot tube traverses, averaging pitot tubes, hot-wire anemometers, ultra-sonic flow meters, and critical flow orifices. The accuracy of these methods is limited when less-than-ideal flow characteristics exist, such as: asymmetric velocity distribution, off-axis flow components due to swirl, turbulence, very low flow, and flow reversal due to wakes or buoyancy. These methods also require the measurement of the cross-sectional area which can be a significant source of error if the shape and dimensions of the sampling section cannot be determined with sufficient accuracy. Tracer gas dilution is a volumetric or whole field method for measuring flow. It does not require the measurement of the cross-sectional area of the duct and, with the exception of flow reversal, it is insensitive to the non-ideal flow characteristics mentioned previously. Flow reversal due to wakes can lead to non-uniform mixing or intermittency in bulk tracer concentrations, therefore care must be taken to understand its impact on the measurement.

The tracer gas dilution method (TGDM) as described by ASTM Standard E 2029–99 [1] uses the constant-injection technique, assuming an ideal gas and constant flow. For this technique, a known concentration of tracer is injected at a constant rate into an upstream location of the flow stream. The tracer becomes mixed and diluted in the flow stream. After steady-state conditions are achieved, the diluted volume fraction of the tracer is measured at a downstream location. Use of the constant-injection technique requires precise metering of the injected tracer, uniform mixing of the tracer into the transport stream, and accurate detection of the diluted tracer. When these requirements are satisfied the volume flow in the duct is given by the following equation:

$$\dot{V} = \frac{X_{T,I} - X_{T,D}}{X_{T,D} - X_{T,U}} \dot{V}_{T,I} \tag{1}$$

Where $X_{T,I}$ is the known volume fraction of the injected tracer; $X_{T,D}$ is the volume fraction of the diluted tracer measured at the downstream sample location; $X_{T,U}$ is the volume fraction of the tracer measured upstream of the injection point or in the ambient environment; and $\dot{V}_{T,I}$ is the measured volume flow of the injected tracer. In the case of a pure tracer, $X_{T,I} = 1.00$.

For decades, the tracer gas dilution method has been widely used for ventilation studies in buildings [2–4]. However, there has been a limited amount of literature that discusses the use of the method to measure flow in large ducts. Of this, a review by Riffat and Cheong summarizes some example investigations as well as the three major variations of the tracer gas dilution method: constant-injection, concentration-decay, and pulsed-injection [5]. For the concentration-decay technique the tracer is initially injected into the flow for some duration and then the injection flow is stopped. The decay of concentration (or volume fraction) of the downstream diluted tracer is monitored for some period and the flow is derived from the decay signal. Tracer is injected for short durations for the pulsed-injection technique and the concentration of downstream diluted tracer is monitored and integrated over the pulse width. The flow is proportional to the ratio of the integrated concentrations of injected tracer to measured downstream

E-mail address: rodney.bryant@nist.gov.

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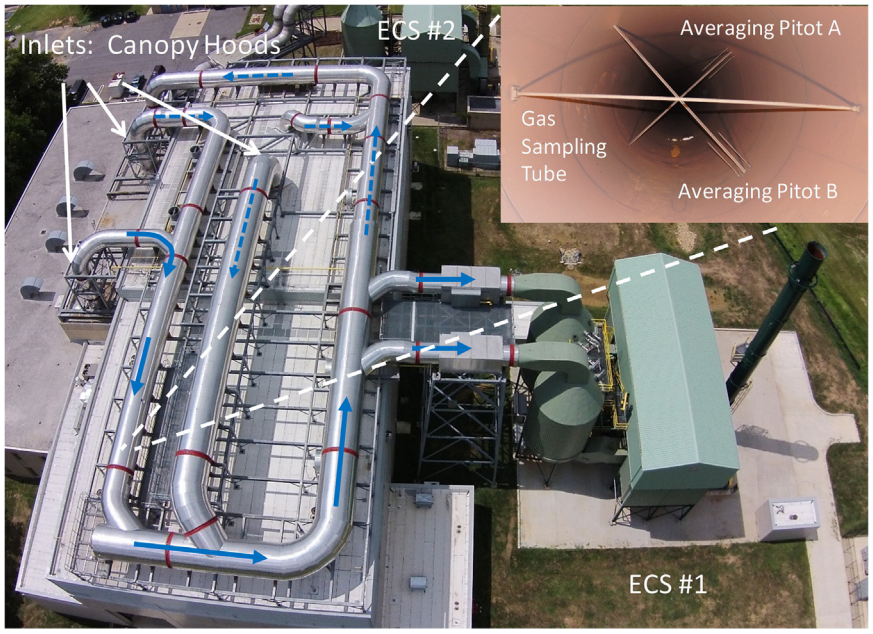

Fig. 1. Overhead view of the National Fire Research Laboratory, its rooftop exhaust ducts, flow measurement location, and emissions control systems (ECSs). Blue arrows mark flow paths from the canopy hoods to the two ECSs. Solid arrows mark the flow path of the present study. Dotted arrows mark flow paths for the other canopy hoods and/or the second ECS. The averaging pitot tubes and the gas sampling tube are shown in the insert.

tracer. A comparison of the three techniques identified constant-injection as the most accurate for duct flows and for building ventilation measurements [6,7]. The constant-injection and pulsed-injection techniques are most appropriate for duct flows, with the pulsed-injection requiring less tracer. However, the requirement for improved measurement accuracy resulted in the selection of the constant-injection technique for the present study.

Studies in laboratory-scale ducts and pipes have demonstrated the performance of the constant-injection technique when compared to hot-wire [8,9], pitot tube [6,9,10], and turbine flowmeter [11] measurements. Despite the promising performance for field application, only a few studies are available which discuss the constant-injection technique in real working ducts and conduits in the field [12–14]. With the exception of a study of flow through a natural gas compressor [14], the afore-mentioned studies for ducts and conduits offer little detail on the estimated uncertainty of the tracer gas dilution method. In most cases, only the discrepancy between the tracer gas dilution method and the comparison measurement, usually a pitot tube or hot-wire, is discussed. It is widely known that pitot tube and hot-wire measurements have limited accuracy in duct flows with asymmetric velocity profiles and off-axis flow components due to swirl and turbulence. Therefore, more examples of detailed uncertainty estimates for the tracer gas dilution method in working duct flows are warranted.

The National Fire Research Laboratory (NFRL), a research facility for the study of large-scale fires and their impact on structures [15], utilizes large fume or flue gas hoods to exhaust the plume of fires as large as 20 MW. The exhaust ducts that service these fume hoods can flow as much as 5100 scmm[1] of air. The facility's primary measurement, heat release rate, is determined by oxygen consumption calorimetry. It is the product of the average heat produced by oxidation due to the fire, the measured deficit of oxygen in the exhaust plume, and the measured flow of the plume through the exhaust duct. Therefore, the uncertainty of the flow measurement can contribute significantly to the combined uncertainty of the heat release rate measurement as demonstrated in a previous study [16]. The exhaust flow is measured using averaging pitot tubes which have limited accuracy in the presence of an asymmetric velocity distribution or a swirling flow as mentioned previously. A study of the exhaust flow in a similar facility revealed that off-axis flow components and asymmetric velocity profiles are likely to exist in these large exhaust ducts [17]. Since the accuracy of the tracer gas dilution method is insensitive to these flow characteristics, the constant-injection technique was tested in the NFRL exhaust ducts.

The main objectives of this study are to estimate the measurement uncertainty of the tracer gas dilution method in a large-scale exhaust duct and evaluate its potential as an independent comparison for NFRL's routine flow measurement, the averaging pitot tubes. An additional objective is to test for uniform distribution of the tracer gas when only passive flow mixing is available. The experiments were conducted in a working facility with large exhaust ducts capable of delivering large volumetric flows. Only a limited number of analogous studies for large-scale flow conduits exist [12,18]. Therefore, this study provides an additional example of an in-the-field application of the tracer gas dilution method for large-scale duct and conduit flows.

2. Material and methods

2.1. Exhaust ducts

The NFRL utilizes large canopy exhaust hoods to remove the plume of fires as large as 20 MW from the facility. These canopy hoods direct the flow into exhaust ducts which service each hood. Two exhaust ducts, 1.98 m ID and 2.44 m ID, run along the roof of the facility and transport the combustion products from the fire to two identical emissions control systems (ECS), Fig. 1. Both ECSs are run simultaneously for flows greater than half capacity, while only one ECS is run for smaller flows. Flow is pulled through the exhaust system by induced-draft fans near the end of each ECS, therefore the operating pressure in the ducts is slightly below atmospheric. The combined system has a volume flow capacity of approximately 5100 scmm or a mass flow capacity of approximately 110 kg/s.

The present study focused on the 1.98 m ID exhaust duct and the flow path servicing the 6 m x 6 m canopy hood, Fig. 1 – solid blue lines. The desired volume flow was achieved by adjusting the position of flow louvers at the induced-draft fans and the position of dilution dampers in the exhaust ducts. Averaging pitot tubes provide flow monitoring for routine operations of the NFRL. Flow settings were determined using these devices, and ranged from 500 scmm to 1200 scmm for the present study.

[1] Standard cubic meters per minute. All flow values are reported for the following standard conditions: T = 273.15 K and P = 101.325 kPa.

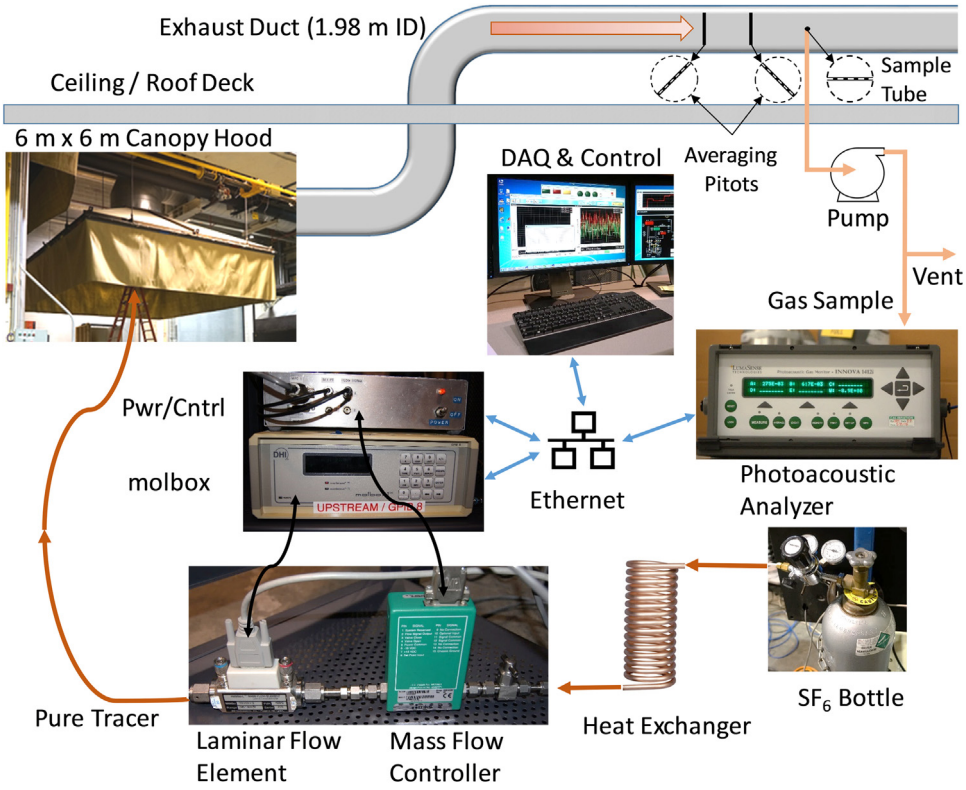

Fig. 2. Schematic of the experimental setup of the volume flow measurement in the 1.98 m ID exhaust duct using the tracer gas dilution method, constant-injection technique.

2.2. Tracer gas dilution – constant injection

A schematic of the tracer injection assembly is shown in Fig. 2. Sulfur hexafluoride (SF_6, 99.99%) flowed from a bottle and through a heat exchanger to a mass flow controller (MKS Instruments, Inc.; Model: M100B53CS1BV).[2] The injection flow of the tracer was selected by adjusting the set-point voltage of the mass flow controller. The tracer flow was measured by a laminar flow element system (Fluke; Model: molbloc-L 1E3-VCR-V-Q with molbox 1 terminal) located downstream of the mass flow controller. This model laminar flow element has been calibrated for SF_6 with NIST PVTt (Pressure Volume Temperature and Time) primary flow standards and demonstrated a standard uncertainty of ± 0.07% of flow reading [19]. The laminar flow element provided the precise and accurate monitoring of tracer injection required for accurate measurement of volume flow.

The tracer flowed to an injection ring located at the inlet of the exhaust duct, inside the canopy hood. Tracer was released through holes drilled into the ring. The ring was 35.6 cm (14 in) in diameter made from 6.35 mm (0.25 in) copper and stainless-steel tubing, with 3.18 mm (0.125 in) diameter holes spaced apart by 50.8 mm, Fig. 3. The injection system was checked for leaks by charging the system with pure tracer up to the point of the mass flow controller; closing the ball-valve; and then confirming that the tracer was not detected in the exhaust flow. Leaks in the injection system, upstream of the metering device, would bias the flow measurement toward lower values. Unusually low flow measurements should be investigated as they could be the result of leaks in the injection system.

After the tracer was injected at the inlet of the exhaust duct, it was transported along the duct, traveling through bends and a straight run with length of more than 10 diameters to allow for mixing of the tracer and the air. At the downstream sampling location, a pump was used to continuously draw gas from a stainless-steel tube, mounted horizontally across the exhaust duct, and transport it to the gas analyzers, Fig. 1 photo insert. The gas sampling tube had 3.2 mm holes drilled every 25.4 cm, therefore the gas sample was spatially integrated across the diameter of the duct. The system is routinely used to sample exhaust gases from fires actively burning under the canopy hoods. These gases contain smoke particulates and increased humidity that may adversely affect some gas analyzers in the system. Therefore, it is routine to condition the gas samples before analysis. Conditioning included filtering to remove particulates and drying to remove water vapor until less than 100 μL/L (100 ppmv) remained. Water vapor was removed using a system of Nafion™ tube dryers (Perma Pure; Model: MG-1228W and PD-200T-72SS). The drying process did not remove SF_6 from the gas sample as confirmed by tests using the calibration mixture. The volume fraction of water vapor in the exhaust gas was measured with a thin film capacitive detector (Vaisala; Model: HMT337) prior to drying the sample. This measurement was used to convert the volume fraction measurements to a wet basis. The gas sample system was assumed to be free of leaks as it had been leak-checked at installation. Leaks in the sample system would bias the flow toward higher values. Unusually high flow measurements should be investigated as they could be the result of a leak further diluting the gas sample.

A portion of the dry sample was directed to a photoacoustic analyzer (LumaSense Technologies; Model INNOVA 1412i) to measure the diluted volume fraction of SF_6 in the transport stream. The analyzer can detect trace amounts of gas in real-time using photoacoustic spectrometry [20,21]. In this technique, the gas sample is irradiated with infrared light where a portion of the light is absorbed by the gas and converted to an acoustic signal that can be detected by a microphone. The analyzer uses optical filters to select which wavelengths of light irradiate the gas sample and therefore which gases are selected for detection. Sulfur hexafluoride was chosen as the tracer due to its strong absorption in the infrared and very low ambient volume fractions

[2] Certain commercial entities, equipment, or materials are identified in this document in order to describe an experimental procedure or concept adequately. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the entities, materials or equipment are necessarily the best available for the purpose.

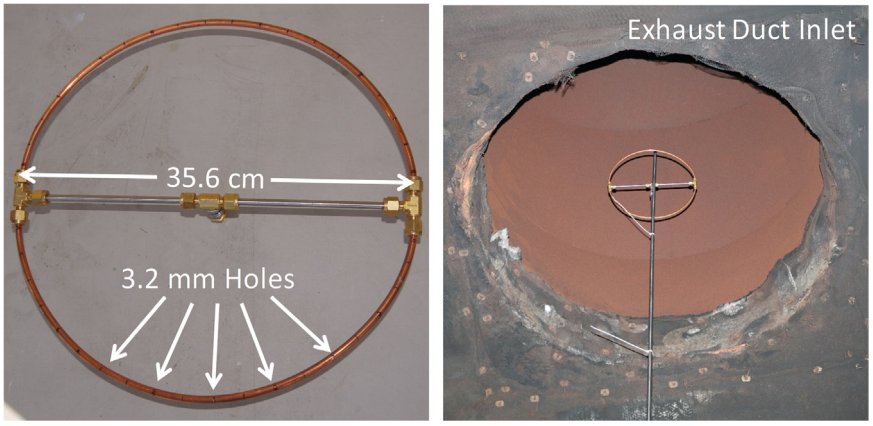

Fig. 3. Tracer injection ring (left photo); and tracer injection ring mounted inside the canopy hood at the inlet of the exhaust duct (right photo).

(0.001 nL/L) [1]. Frequent use of SF_6 as a tracer is not recommended as it is a greenhouse gas with a high potential for global warming. However, SF_6 is one of the few tracer gases detectable in the range of (0.001–100) nL/L that is nontoxic and nonreactive. These features made SF_6 the logical choice for the tracer, since the present study investigated large volume flows, with requirements for generating manageable tracer injection flows, maintaining personal health and safety, and preserving the condition of existing equipment.

Estimates of the appropriate injection volume flow of SF_6 were based on Eq. (1) and the following factors: 1) the measurement range and detection limit of the photoacoustic analyzer used to measure the diluted volume fraction of the tracer; 2) the volume fraction of the gas mixture used to calibrate the photoacoustic analyzer, 3) the measurement range of the laminar flow element used to monitor the volume flow of the injected tracer, and 4) the operating range of the mass flow controller used to control the injection flow. The detection limit of the photoacoustic analyzer for SF_6 was 6 nL/L (6 ppbv). The calibration mixture was a high-pressure bottle of 275 nL/L ± 1 nL/L SF_6 (275 ppbv ± 1 ppbv SF_6) with a balance of dry air. This mixture was introduced directly to the photoacoustic analyzer to perform a single-point field calibration of the instrument prior to each experiment. Therefore, injection volume flows were selected to generate diluted volume fractions within ± 20% of the calibration mixture, Fig. 4. For the range of duct flows, 500 scmm to 5100 scmm, a flow metering device capable of delivering up to 1.70 slpm (standard liters per minute) of tracer gas was required to generate the targeted downstream volume fractions. Maximum exhaust flow for this study was approximately 1200 scmm.

The experimental procedure consisted of: 1) adjusting the exhaust flow to the desired setpoint by adjusting the flow dampers, 2) adjusting the tracer injection flow to get the optimum amount of diluted tracer for the exhaust flow (Fig. 4), 3) monitoring the flow measurements from the averaging pitot tubes and the tracer dilution measurement, and 4) recording the flow measurements for steady conditions. In a typical experiment, measurements were conducted at four different setpoints of flow, with repeats at two or more setpoints. Seven repeat experiments were conducted on seven different dates, which generated more than 40 pairs of flow measurements that spanned the range of routine volumetric flows for the exhaust hood. Because SF_6 decomposes into toxic compounds at high temperatures, all experiments were conducted without a fire present, hence without heating and using only the ambient air as the exhaust flow.

3. Results and discussion

3.1. Component uncertainty

Each measurement of tracer gas volume fraction was for a dry gas, as the gas samples were conditioned to remove water vapor prior to being analyzed. Therefore, Eq. (1) was revised to account for the water vapor in the flow, $X_{H2O,i}$; computing the volume flow for the wet conditions in the exhaust duct:

$$\dot{V} = \frac{X_{T,I} - X_{T,D}(1 - X_{H2O,D})}{X_{T,D}(1 - X_{H2O,D}) - X_{T,U}(1 - X_{H2O,U})}\dot{V}_{T,I} \quad (2)$$

An uncertainty analysis was performed to estimate the combined uncertainty of Eq. (2). Assuming the input measurements were mutually independent, the following equation was applied to estimate the

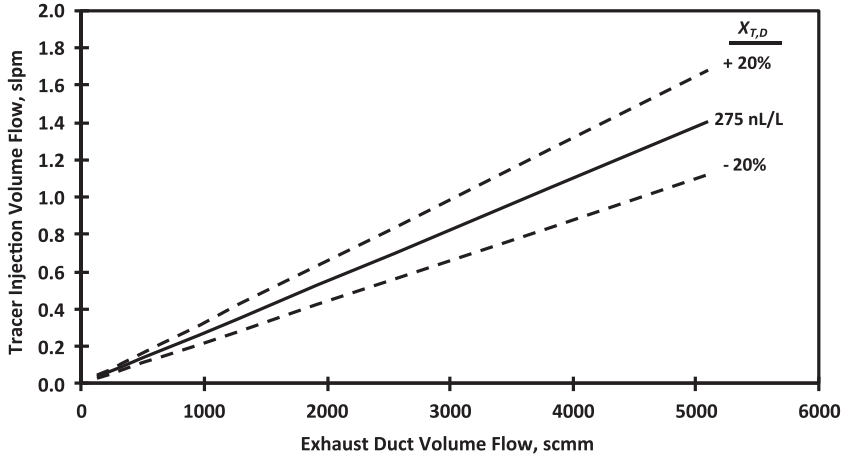

Fig. 4. Estimates of tracer injection volume flow required to generate optimal tracer volume fractions downstream.

Table 1
Example of an uncertainty budget for the volume flow determined using the TGDM.

Measurement Component, x_i	Value	$u(x_i)/x_i$	s_i	% Contribution
Injected Tracer Volume Fraction, $X_{T,I}$ (L/L)	1.0000	0.0001	1.0	0.0
Downstream Tracer Volume Fraction, $X_{T,D}$ (nL/L)	276	0.0112	− 1.0	67.7
Upstream Tracer Volume Fraction, $X_{T,U}$ (nL/L)	0	–	0.0	0.0
Injected Tracer Volume Flow, $\dot{V}_{T,I}$ (scmm)	3.185×10^{-4}	0.0007	1.0	0.3
Downstream Water Volume Fraction, $X_{H2O,D}$ (L/L)	0.00884	0.0100	0.0089	0.0
Upstream Water Volume Fraction, $X_{H2O,U}$ (L/L)	0.00894	0.0100	0.0	0.0
Repeatability (SDOM)	–	0.0060	1.0	19.5
Degree of Mixing	–	0.0048	1.0	12.5
Exhaust Volume Flow, $\dot{V}_E$ (scmm)	**1164**	**0.0136**	**Standard, $u_c(y)/y$**	
		0.0272	**Expanded, $U_c(y)/y$**	

combined relative standard uncertainty:

$$\frac{u_c(y)}{y} = \sqrt{\sum_{i=1}^{N} s_i^2 \left(\frac{u(x_i)}{x_i}\right)^2} \tag{3}$$

The relative standard uncertainty, $u(x_i)/x_i$, for each input measurement, x_i, used to compute the volume flow, $y = \dot{V}$, is listed in Table 1. The non-dimensional sensitivity coefficient, given as,

$$s_i = \frac{\partial y}{\partial x_i}\frac{x_i}{y} \tag{4}$$

is also listed to reflect the weighting applied to the standard uncertainty of each component. The combined relative standard uncertainty is multiplied by a coverage factor of 2.0 to estimate the combined relative expanded uncertainty, $U_c(y)/y = 2.0\, u_c(y)/y$, with a confidence level of approximately 95%. Standard uncertainty estimates for the component measurements in Table 1 represent the accuracy and repeatability of the response of each instrument for a well-controlled and constant input.

Table 1 shows that the greatest contribution of uncertainty comes from the downstream measurement of tracer volume fraction. Estimated relative standard uncertainty for the measurement is ± 0.0112. This is the combined result of the relative standard uncertainty of the calibration mixture, ± 0.002, and relative repeatability (1σ) result for the photoacoustic analyzer, ± 0.011, at volume fractions close to the calibration mixture, 275 nL/L. The relative repeatability improved to ± 0.006 for a higher volume fraction measurement, 500 nL/L, which was consistent with the manufacturer's repeatability estimate, ± 0.005. Having a higher concentration calibration mixture with low uncertainty would help to reduce the combined uncertainty. Component uncertainty estimates listed in Table 1 do not include the repeatability of the measurement under the conditions of the experiment. This contribution to uncertainty propagates to the final result, the exhaust duct volume flow, and is examined in the following section.

3.2. Measurement repeatability

The constant-injection technique of the tracer gas dilution method works best when the flow in the duct is stable. For this study, measurements were continuously logged at an update rate of 1 Hz, with exception of the tracer volume fraction which had an update rate of 0.025 Hz (1 sample every 40 s). After steady-state was achieved, measurements were tagged as being suitable for analysis. Volume flow measurements reported here are the average of at least 10 consecutive measurements at steady conditions. Because of the slower update rate of the photoacoustic analyzer, a minimum measurement period of 7 min was required.

The relative standard error or standard deviation of the mean (SDOM) is the appropriate measure of repeatability for the reported measurements. The repeatability of the volume flow measurement is plotted in Fig. 5. For the range of flow conditions in this study, the relative repeatability was ± 0.006 on average. Except for a few outliers, the relative repeatability did not exceed ± 0.013. This estimate of measurement repeatability accounts for fluctuations from all components of the experiment, which includes fluctuations due to the exhaust flow, tracer injection flow, and instrumentation.

3.3. Mixing confirmation

The accuracy of the tracer gas dilution method depends on the degree of mixing of the tracer with the transport stream. Uniform mixing ensures that dilution of the tracer represents the overall flow of the transport gas. To reduce the potential for bias error, the gas sample was simultaneously drawn from multiple locations in the flow to average any non-uniformity in the distribution of the tracer. This provided a spatially integrated gas sample. In addition, experiments were conducted at the start of the test series to evaluate how well the tracer mixed with the flow as well as the effectiveness of the sampling strategy to collect a sample that represented the overall dilution.

For the mixing confirmation experiments, tracer was injected at the inlet of the exhaust duct from a single point, a 9.53 mm (ID) stainless steel tube. The exhaust flow and tracer injection rate were held constant while the injection tube was relocated to different quadrants of the injection plane. If the tracer does not completely mix with the flow at the downstream sample location, then any change in the location of the tracer injection should influence the distribution of the tracer at the sample plane downstream. Even though the volume flow is held steady, this would result in an erroneous change in the measured volume flow; especially if the tracer was sampled at a single point. However, a spatially integrated sample, as for the present case, should be insensitive to small changes in the downstream distribution of the tracer and the resulting volume flow measurement (TGDM) should remain steady. This was true as demonstrated by the time trace in Fig. 6 which shows a steady volume flow during the period of relocating the tracer injection point.

Volume flow measurements are plotted with respect to injection location at the inlet in Fig. 7. The injection locations, illustrated in the top-right schematic, were at the center of the circular inlet, near the wall of the inlet for the four quadrants, and in the middle of the northwest quadrant. Average volume flow is plotted for 10 or more measurements at each injection location. For the set of injection locations, the relative standard deviation is ± 0.0048 (± 3.6 scmm, dashed lines), which is approximately the relative SDOM of the individual volume flow measurements, represented by the error bars in Fig. 7 and the SDOM values near 750 scmm in Fig. 5. This demonstrates that the distribution of measurements for different injection locations is consistent with the distribution of repeat measurements for constant conditions. The analysis is analogous to traversing a single point sample along a chord of the downstream cross section. The results suggest that either, or both, of the following are true: 1) the spatially integrated sample is insensitive to changes in the distribution of the tracer at the sample location; 2) the tracer is well mixed at the sample location. The result is consistent with the guidance that one or two bends in a flow

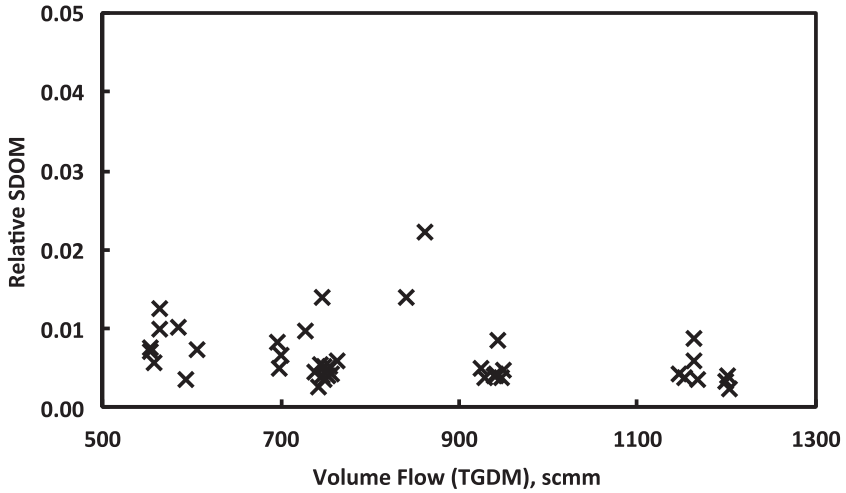

Fig. 5. Repeatability of the reported mean volume flow measurements.

path of 10 hydraulic diameters or more should produce a deviation in the distribution of the tracer across the duct of less than 2%; indicating that passive mixing is adequate [22]. When passive mixing is not adequate, other means of enhancing the mixing may be utilized. Recently investigators demonstrated an enhanced-mixing technique that reduced the distance to achieve sufficient mixing from the recommended 10 hydraulic diameters [1] to 7 hydraulic diameters [10].

The distribution of volume flow in Fig. 7 is less than 0.5%, suggesting that sufficient mixing was achieved. However, a conservative approach to estimating the uncertainty has been applied. The measurement uncertainty due to mixing was estimated as the relative standard deviation of volume flow as determined by this mixing study. This estimate for systematic uncertainty was added in quadrature with other component estimates to estimate the combined uncertainty of the volume flow measurement.

3.4. Combined Uncertainty

Estimates of measurement uncertainty for the exhaust duct volume flow determined using the tracer gas dilution method are plotted in Fig. 8. For the range of flow and the experimental conditions of this investigation, the relative expanded uncertainty was ± 0.028 on average, and did not exceed ± 0.035, except for a few outliers. The major contribution of uncertainty comes from the measurement of downstream tracer volume fraction, measurement repeatability, and the degree of mixing of the tracer with the flow, as shown in Table 1. The measurement of downstream tracer volume fraction, or the photoacoustic analyzer measurement, had the greatest contribution at 67.7%, followed by the measurement repeatability at 19.5%, and the degree of mixing at 12.5%. The uncertainty contribution of the injected volume flow of tracer was small due to the low uncertainty of the laminar flow element, ± 0.0007. For this experiment, tracer injection measurement uncertainty greater than one third of the uncertainty for the tracer volume fraction measurement, ± 0.0112/3, would have resulted in larger estimates of combined uncertainty. Typical electronic mass flow controllers have an accuracy of ± 1%. Therefore, using a low uncertainty device like the laminar flow element is one approach to controlling the measurement uncertainty. The repeatability of the photoacoustic analyzer contributed significantly to the combined uncertainty. It is also included in the overall repeatability of the volume flow measurement. The conservative approach of twice considering the repeatability of the photoacoustic analyzer applies until more data is gathered for this application of the instrument. As stated previously, the repeatability of the instrument improved for a higher concentration calibration mixture. Therefore, a low uncertainty calibration mixture with a greater concentration of SF_6 will help to lower uncertainty.

The repeatability of the volume flow measurement depends on the design of the experiment and the experimental conditions. A few of the experiments had greater measurement noise than others. This resulted in outliers in the combined uncertainty estimates, those that exceeded ± 0.035. The cause for these outliers is unknown. In cases where the measurement noise is consistently present and cannot be

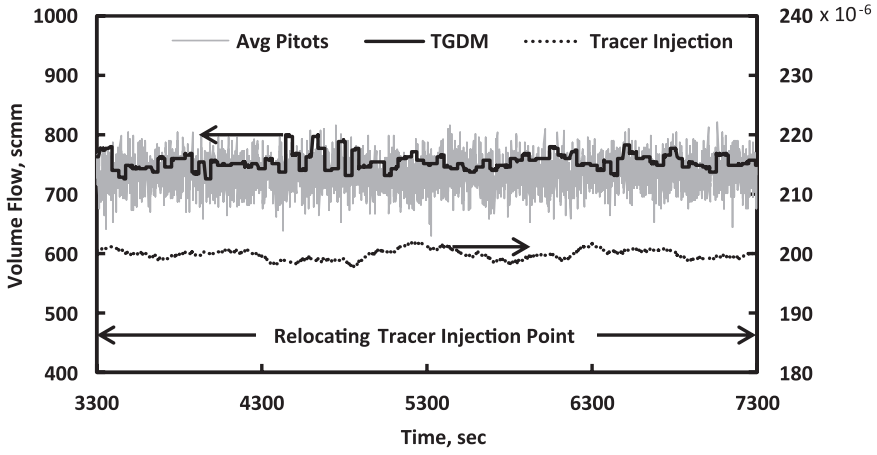

Fig. 6. Time trace for steady conditions of exhaust flow and tracer injection flow demonstrate a steady exhaust flow measurement by the TGDM during relocation of the tracer injection point at the inlet plane.

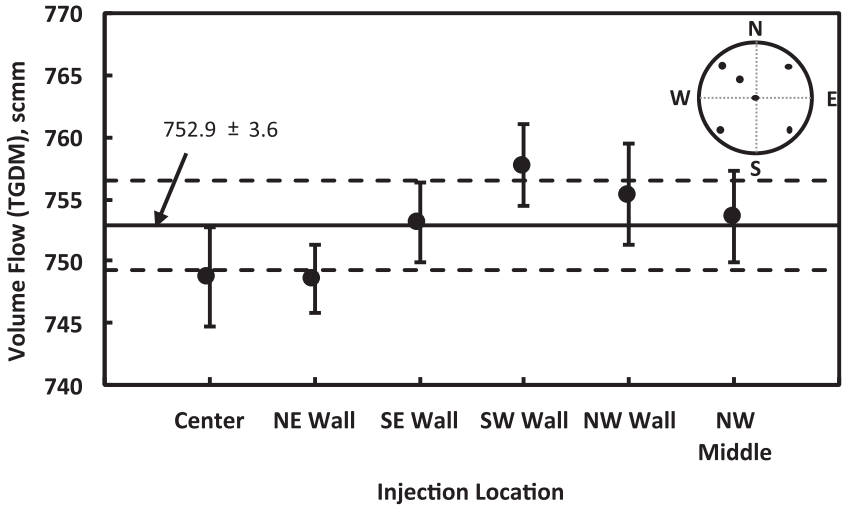

Fig. 7. Confirmation of uniform mixing of the tracer with single point injection at various locations at the exhaust duct inlet. Each point is the mean of 10 or more measurements, and the SDOM is represented by the error bars.

reduced, increasing the number of measurements will help to reduce the uncertainty due to the measurement noise. The uncertainty due to the degree of mixing contributed more than 10% to the combined uncertainty. This contribution will depend on the experimental configuration and therefore should be evaluated early in an experimental test series. A low degree of mixing can lead to significant measurement error. Simultaneous sampling from multiple locations in the downstream sample plane are recommended to reduce the uncertainty due to tracer mixing. At the start of any test series, preliminary experiments to confirm uniform mixing or effective sampling are also recommended.

A linear response for volume flow is anticipated for the tracer gas dilution method. This was confirmed for the range of volume flow investigated in this study. Fig. 9 compares the set-point of the exhaust flow, measurements from the averaging pitot tubes, to the flow measured using the tracer gas dilution method. The data demonstrates a linear response between set-point and measured flow. For best performance, ASTM E 2029 recommends that tracer gas dilution experiments are designed to deliver a tracer volume fraction at the downstream location that is within ± 20% of the volume fraction of the gas mixture used for the single-point field calibration. In this case $X_{T,D}$ = (275 ± 55) nL/L [1]. Since SF_6 is a strong absorber in the infrared, a linear response of the photoacoustic analyzer that extended beyond this range was anticipated. Higher injection flows were used for a subset of experiments to induce higher downstream volume fractions of tracer, 330 nL/L ≤ $X_{T,D}$. Fig. 9 demonstrates that the volume flow measurements for this extended range of downstream tracer volume fraction follow the same linear response. This suggests, for a tracer like SF_6, the linear response of the tracer can be extrapolated beyond the field calibration without a loss of measurement performance.

The average discrepancy between averaging pitot tube and tracer gas dilution measurements of volume flow was 2.7%. This is within the limits of the expanded uncertainty for the tracer gas dilution method and therefore demonstrates agreement of the two methods. This level of agreement further demonstrates that the tracer gas dilution method is a good choice for independent confirmation of routine flow measurements in large-scale exhaust ducts or conduits. In cases where less-than-ideal flow characteristics such as asymmetric velocity distribution, flow swirl, or very low flow are known to exist and compromised accuracy of routine measurements such as pitot tubes, averaging differential pressure devices, or ultra-sonic flow meters is anticipated, the method can be applied to increase measurement confidence.

4. Conclusions

The constant-injection technique of the tracer gas dilution method was applied in the duct of a large-scale flue gas exhaust system. An estimate of the measurement uncertainty for this application of the method was computed by performing an uncertainty propagation of

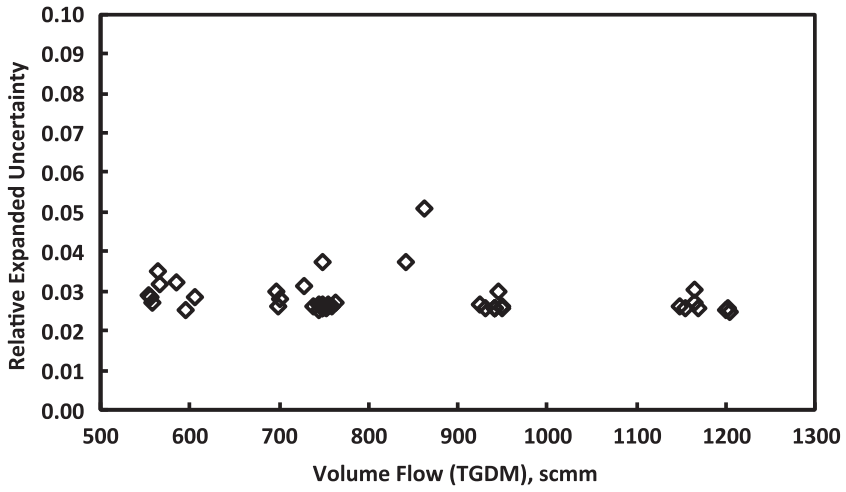

Fig. 8. Estimated uncertainty for the exhaust duct volume flow measurement using the TGDM.

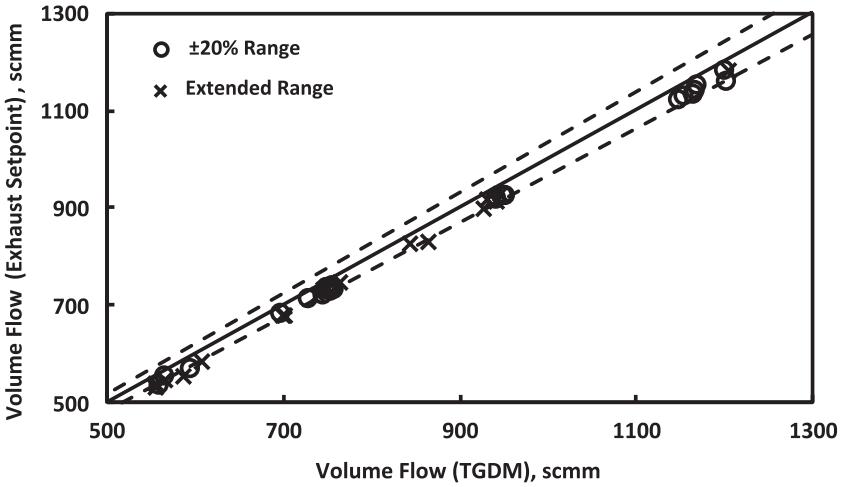

Fig. 9. Comparison of exhaust duct set-point flow (averaging pitot tubes) and exhaust flow determined using the TGDM. The solid line represents one-to-one agreement, while the dashed lines represent estimated limits of expanded uncertainty for the TGDM, ± 3.5%.

component measurements, evaluating the degree of tracer mixing, and measuring the repeatability of the test method. For the example considered in this study, the relative expanded uncertainty of the volume flow measurement using the tracer gas dilution method was on average ± 0.028 and typically less than ± 0.035. Measurement uncertainty for the diluted volume fraction of tracer had the greatest contribution to the combined uncertainty, followed by the measurement repeatability, and the degree of mixing. Increasing the number of measurements used to compute the mean will help to reduce the uncertainty due to repeatability. Designing measurements that confirm uniform mixing will also help control measurement uncertainty. The discrepancy between the routine flow measurement for the exhaust duct, the averaging pitot tubes, and the tracer gas dilution method was within the uncertainty limits of the method, therefore demonstrating agreement between the two measurements. The level of measurement uncertainty reported for this example and the agreement between the two measurement methods demonstrate that the constant-injection technique of the tracer gas dilution method can be applied as an independent comparison or quality check for routine flow measurement methods in large-scale exhaust ducts or conduits. This method is especially useful when the accuracy of the routine measurement is in question. Advances in the measurement instrumentation required for this method, like portable real-time trace detection of gases, have simplified its application. Studies that describe field applications of the tracer gas dilution method in ducts and conduits and that report measurement uncertainty for current state-of-the-art instrumentation have been limited. More studies like this that explore larger-scale flows in closed conduits such as power plant exhaust stacks, combined liquid and gas-phase flows, or other tracers such as helium, are necessary to evaluate the benefits of the method for future applications.

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