NIST Special Publication 1228

Improving Measurement for Smokestack Emissions – Workshop Summary

Rodney A. Bryant
Aaron N. Johnson
John D. Wright
Tamae M. Wong
James Whetstone
Michael R. Moldover
Scott Swiggard
Chris Gunning
David L. Elam, Jr.
Thomas Martz
Eric Harman
David Nuckols
Liang Zhang
Woong Kang
Salvator Vigil
Iosif Shinder
Keith Gillis

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1228

NIST
National Institute of
Standards and Technology
U.S. Department of Commerce

NIST Special Publication 1228

Improving Measurement for Smokestack Emissions – Workshop Summary

Rodney A. Bryant
Fire Research Division
Engineering Laboratory

Aaron N. Johnson
John D. Wright
Sensor Science Division
Physical Measurement Laboratory

Tamae M. Wong
James Whetstone
Special Programs Office

Michael R. Moldover
Sensor Science Division
Physical Measurement Laboratory

Scott Swiggard
Golden Specialty, Inc.

Chris Gunning
American Association for Laboratory Accreditation

David L. Elam Jr.
TRC Companies, Inc.

Tom Martz
Electric Power Research Institute

Eric Harman
Colorado Engineering Experiment Station

David Nuckols
Dominion Energy

Liang Zhang
National Institute of Metrology, China

Woong Kang
Korea Research Institute of Standards and Science

Salvator Vigil
Teledyne

Iosif Shinder
Keith Gillis
Sensor Science Division
Physical Measurement Laboratory

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1228

September 2018

U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Institute of Standards and Technology
Walter Copan, NIST Director and Undersecretary of Commerce for Standards and Technology

National Institute of Standards and Technology Special Publication 1228
Natl. Inst. Stand. Technol. Spec. Publ. 1228, 71 pages (September 2018)
CODEN: NSPUE2

This publication is available free of charge from:
https://doi.org/10.6028/NIST.SP.1228

Abstract

The complex flow conditions inherent in power plant smokestacks make accurate flow measurements challenging, which in turn limits the accuracy of hazardous emissions measurements. While stack composition measurements are assessed daily via comparison to a certified gas standard, the flue gas flow meter is only calibrated once a year via the flow relative accuracy test audit (RATA). In most cases the flow RATA is performed using an S-type pitot probe whose performance can be adversely affected by the complex flow conditions (*i.e.*, asymmetric velocity profile and swirling flow) typical in stacks. NIST sponsored a workshop to discuss the current and future flow measurement needs with stakeholders in the electric power generation industry. The meeting included regulators, owners of stationary sources, stack testers, equipment manufacturers, national metrology institutes from other countries, flow measurement laboratories, and accreditation bodies. During the workshop participants gave presentations on several topics including accreditation, modifications to regulations that will improve flow measurement uncertainty, flow RATA accuracy for the S-type pitot probe as well as for the prism probe and spherical probe, and the accuracy of different continuous emissions measurement systems (CEMS) in stack applications. NIST gave tours and presented results from its research facilities specifically designed to improve the accuracy of stack flow measurements. At several points the workshop participants divided into small groups to discuss presentations made by invited speakers and NIST researchers. Group discussions centered around three topics including 1) Air Emission Testing Bodies (AETB), 2) Accuracy of RATA and CEMS Flow Measurement Methods, and 3) how NIST research facilities can be best used to help improve flow measurements in industrial applications. Of particular interest to the group was a non-nulling method developed by NIST that could potentially reduce RATA test time while still improving accuracy to levels on the order of 1 %. In addition, participants recommended that NIST work with the industry to validate its findings with full-scale testing of X-pattern flow monitors, non-nulling 3D probes, and the CO_2 emissions mass balance on actual power plant stacks. The content of the presentations and the results of group discussion are summarized in this document.

Key words

AETB, Carbon Mass Balance, CEMS, Carbon Dioxide, Greenhouse Gas, Emissions, Flow Measurement, Method 2F, National Fire Research Laboratory, Non-nulling, Prism Probe, RATA, S-probe, Scale-Model Smokestack Simulator, Spherical Probe, Tracer Gas Dilution.

Table of Contents

List of Tables

List of Figures

1. Introduction

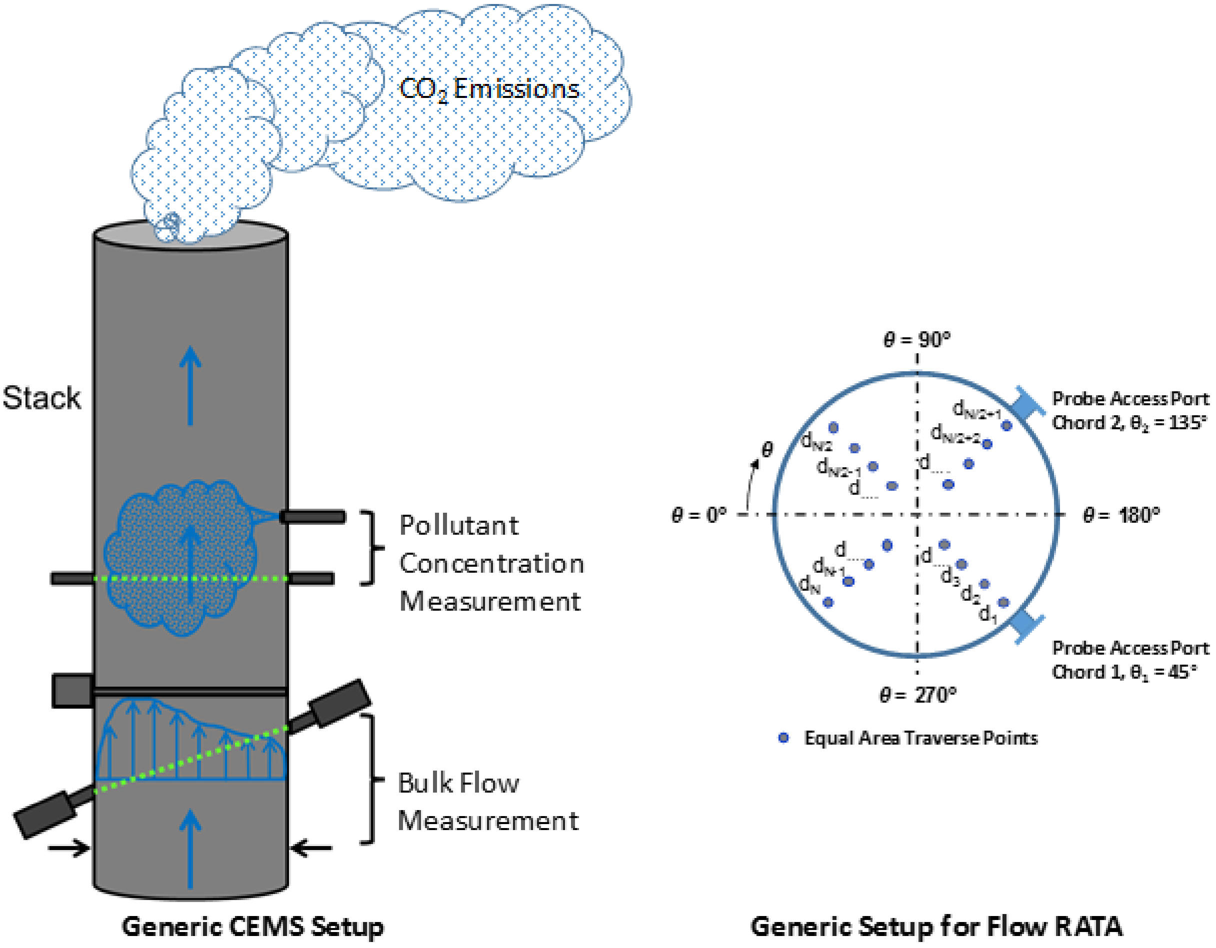
Most of the nation's electricity is generated by burning hydrocarbon fuels. This source of energy continues to serve the economic demand for stable, reliable, and cost effective electric power. Accurate and reliable emissions monitoring from smokestacks is thus vital for complying with regulations and minimizing environmental and health effects. The role of the National Institute of Standards and Technology (NIST) in supporting this industry is to provide the technical tools and guidance to improve the accuracy in emissions measurements and to minimize the uncertainty in operating conditions, testing, and analysis. On June 28 and 29, 2017, NIST hosted the workshop on Improving Measurement of Smokestack Emissions, at the Gaithersburg, Maryland campus. This was the second such workshop hosted at NIST, with the first being held in 2015. [1] Flow measurement accuracy was the focus of discussion, with the objective of the workshop being to provide a forum to exchange experiences, best practices, and ideas related to current and emerging issues with measuring emissions from smokestacks. The workshop gathered experts from the electric power generation industry including the Electric Power Research Institute, manufacturers of smokestack flow meters, companies that perform in situ calibrations of smokestack flow meters, the US Environmental Protection Agency (EPA), and other national metrology institutes. The workshop participants discussed the measurement infrastructure that is presently in use, reviewed recent NIST research on the uncertainty of and possible improvements to smokestack emission measurements, and provided recommendations for the direction of future work.

1.1. Background

The waste combustion gases from coal-fired power plants (CFPPs) are exhausted into vertically-oriented, large diameter (e.g., D > 5 m) smokestacks. These stacks are designed to disperse pollutants into the atmosphere so that the effects of pollution at the ground-level are minimized. To quantify the amount of pollutants released into the atmosphere the bulk flow in the stack must be accurately measured. Stacks, however, are not designed to facilitate accurate flow measurements. The network of elbows, reducers, fans, etc. upstream of the stack inlet result in complex flow conditions that make accurate stack flow measurements difficult. The fact that the flue gas is hot (around 50 °C), saturated, and asphyxiating only complicate the measurement problem. Nevertheless, an accurate measurement of the bulk flow is critical to controlling emissions of greenhouse gases (GHGs) and other hazardous pollutants.

Pollutant emission rates are the product of the bulk flow and the pollutant concentration. Continuous emissions monitoring systems (CEMS) are measurement instrumentation permanently installed in the smokestack to continuously measure pollutant concentration (e.g., CO_2) and the bulk or volumetric flow of gas through the smokestack, as demonstrated in Figure

1. EPA requires periodic (annual) calibration of a smokestack's CEMS using test procedures called relative accuracy test audits (RATA). The procedures are developed by the EPA and used by certified testers to measure the flow velocity and concentration in a smokestack. RATA testers temporarily install their measurement equipment in a smokestack to calibrate CEMS equipment. The flow RATA is a detailed measurement of the average gas velocity and hence the volume flow rate in the smokestack. The procedure uses pitot probes to measure the velocity of the stack gas at discrete points at a cross section of the smokestack, as shown in Figure 1. The principle of operation of the pitot probe is: differential pressure across the pitot ports is correlated to the fluid velocity via a calibration factor. Of the three types of pitots, standard L-type, S-type, and three-dimensional, the S-type is the most widely used for flow RATAs. The pitot probes are traversed along two orthogonal chords and the velocity measurements are used to generate a representative sample of the flow distribution. Volumetric flow is determined by averaging the point velocity measurements and multiplying by the cross-sectional area. The relative accuracy is the percent difference between the volumetric flow determined by the RATA with that determined by the CEMS.



Generic CEMS Setup **Generic Setup for Flow RATA**

Figure 1 Schematic of a generic setups for stack mounted CEMS (left) and flow RATA (right).

The flow RATA is the reference standard for the flow measurement; hence the CEMS measurement is only as good as the flow RATA. Current flow RATA measurements are not rigorously traceable to NIST primary flow standards. As such, the flow RATA cannot determine the absolute uncertainty of a CEMS measurement, but instead only provides relative accuracy between the EPA Method and the CEMS flow monitor. Even if this difference is small, it does not guarantee a low uncertainty flow measurement. A CEMS flow monitor that is recurrently calibrated against the same type of probe in the same flow conditions could yield consistent good agreement with RATA results, and yet have a significant uncertainty. To quantify the absolute uncertainty of CO_2 emissions measurements requires establishing rigorous metrological traceability.

Since 1992 NIST has supported accurate concentration measurements by providing certified gas mixtures called NIST Traceable Reference Materials (NTRM) to the stack testing community. These NTRMs are traceable to NIST primary standards at specified uncertainty levels. The NTRMs are often used by specialty gas suppliers to develop EPA protocol gases, which in turn are used for stack concentration measurements. NIST has certified over 19,000 gas mixtures since the inception of the NTRM standards program in 1992. [2] In 2006 and again in 2008 NIST audited EPA protocol gas suppliers to help ensure that the concentrations of protocol gases were within their required accuracy specifications. [3-6] In this way, the measurement process for gas concentration begins with NIST establishing traceability and concludes with NIST (at least periodically) verifying the accuracy of EPA protocol gas concentrations.

In contrast, NIST has not been involved in establishing or ensuring the accuracy of stack flow measurements for more than 3 decades. Yet, flow measurement accuracy is potentially more significant than concentration measurements. An inaccurate concentration measurement only affects the mass calculation of that one pollutant, while an inaccurate flow measurement is multiplied by all the concentration measurements and therefore leads to inaccurate values of all emitted pollutants. Perhaps more importantly, all pollutant measurements are biased in the same direction as the flow error.

Recently, NIST has leveraged its expertise in flow measurement and its research facilities to address the challenges involved in accurately measuring stack flows. Research is ongoing to evaluate and improve the-state-of-the-art for stack flow measurements as well as to evaluate and develop new flow measurement methods. New facilities such as the Smokestack Simulator, and existing facilities like the NIST Wind Tunnel and the National Fire Research Laboratory are being utilized for this research. NIST has also organized and hosted past workshops [1], providing a forum for a diverse group of industry stakeholders to share their perspectives on the strengths and weakness of current flow measurement protocols and discuss potential improvements.

1.2. Workshop Format

Announcements and invitations were extended to stakeholders representing the industry for stationary source air emissions. The workshop was attended by more than 30 industry stakeholders. Workshop participation included technical and research staff from the electric power generation industry, CEMS equipment manufacturers, RATA testing companies, foreign and domestic national metrology institutes, state and federal environmental regulatory agencies, commercial flow calibration laboratories, and accreditation agencies. Workshop speakers were invited to give presentations on the following range of topics related to CEMS and RATAs:

- Calibration and uncertainty of pitot probes used in RATAs
- Innovative flow measuring techniques
- Measurement traceability
- Advanced multipath ultrasonic meters for improved flow measurement
- Concentration and flow rate measurement uncertainty, CEMS and RATAs
- Fuel calculation method for determining CO_2 emissions
- Challenges of accurately measuring smokestack emissions

The final agenda of presentations was organized into the following three sessions:

- Air Emission Testing Bodies
- Flow Measurements
- NIST Research Facilities

Session subtopics included accreditation, measurement uncertainty and traceability, evaluating measurement performance, measurement challenges, and development of new measurement methods. The sessions ended with a period for discussion, facilitated with questions surrounding the subtopics.

This report structure mirrors the workshop agenda. It contains sections for each workshop session, and these sections contain a summary of each presentation – an extended abstract prepared by each speaker. The content of the workshop discussions for each session is also summarized. The discussion summary captures a sample of the industry’s thoughts and perspectives on specific topics and ways to improve smokestack emissions measurements.

2. Overview of the Greenhouse Gas Measurements Program at NIST

Presenter: John Wright, James Whetstone, Aaron Johnson, Rodney Bryant, Michael Moldover – NIST

2.1.1. Introduction

The National Institute of Standards and Technology is studying the measurement of flow from smokestacks so that scientists and society have reliable data for informed decisions. NIST is the national metrology institute for the United States, a non-regulatory agency with a mission to develop measurement methods that are reliable, economical, traceable, and with uncertainty levels that are fit for their purpose.

The NIST program for Greenhouse Gas Measurements has five sub-programs:

> Advanced satellite calibration standards to enable accurate and traceable measurements by Earth-viewing satellites for surface temperature, solar radiation, reflectance, and ocean color.
>
> Measurement tools and testbeds for urban emissions quantification. Researchers are using networks of sensors distributed in cities to map sources and sinks of CO_2, better understand the CO_2 budget, and reconcile data on emission sources with atmospheric inventories.
>
> Standard reference gases and property databases. The NIST Traceable Reference Materials program sells gas cylinders with known concentrations of CO_2, SO_2, and NO_X that are used to calibrate gas chromatographs that measure stack emissions. The NIST Reference Fluid Thermodynamic and Transport Properties database (REFPROP) provides properties for a wide range of pure and mixed gases.
>
> Carbonaceous aerosol research studies the radiative forcing effects of aerosol particulates, an important input to global temperature models.
>
> Stationary or point source metrology research is improving the accuracy of emission measurements from the smokestacks of power plants burning fossil fuels; this workshop is dedicated to this subject.

The state of the art and the challenge of making low uncertainty CO_2 emission measurements are illustrated by comparing the results from two measurement methods, 1) pre-combustion and 2) post-combustion. [7] The pre-combustion (or fuel calculation) method measures the carbon content and the mass of fuel burned to calculate the output of CO_2 (assuming complete combustion). The post-combustion method uses smokestack flow and gas composition data from a continuous emissions monitoring system (CEMS). The flow is usually measured with a single path ultrasonic time-of-flight flow meter installed in the smokestack. Composition is measured with a gas chromatograph. A comparison of the two methods for more than 1000 power plants burning coal or residual fuel oil, Figure 2, shows a standard deviation of 20 % for the difference between the two methods.

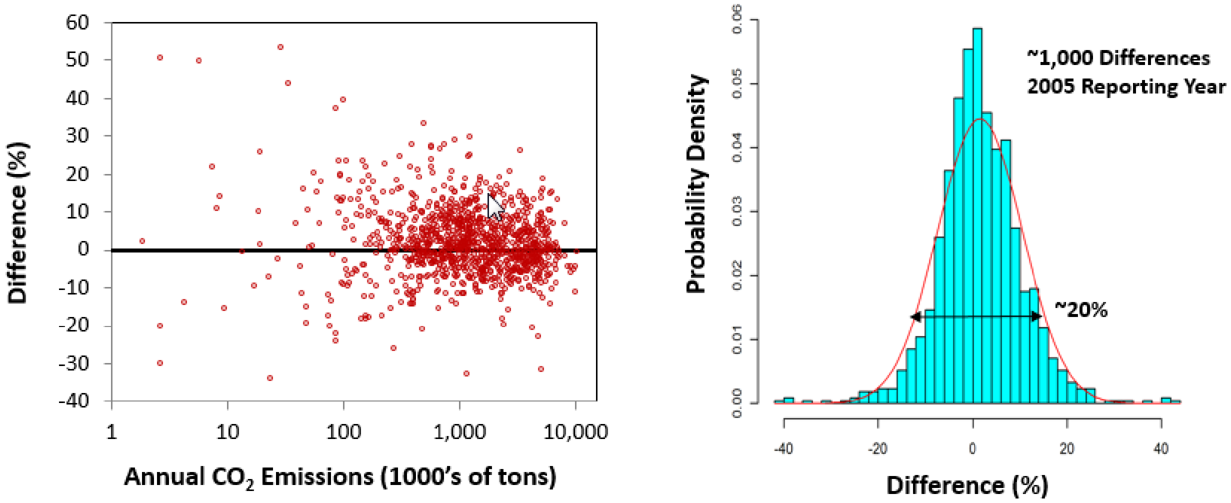


Figure 2 Difference in CO$_2$ emissions for the pre- and post-combustion methods based on Energy Information Administration data from the year 2005.

The differences between pre- and post-combustion measurements are not surprising. The pre-combustion approach works well for natural gas, but accurate measurements of the carbon content of coal are complicated by composition inhomogeneity and by moisture content. For the post-combustion method, stack flow measurements are challenging due to non-ideal velocity profiles and swirl from bends, manifolds, and short runs of straight stack, as demonstrated in Figure 3.

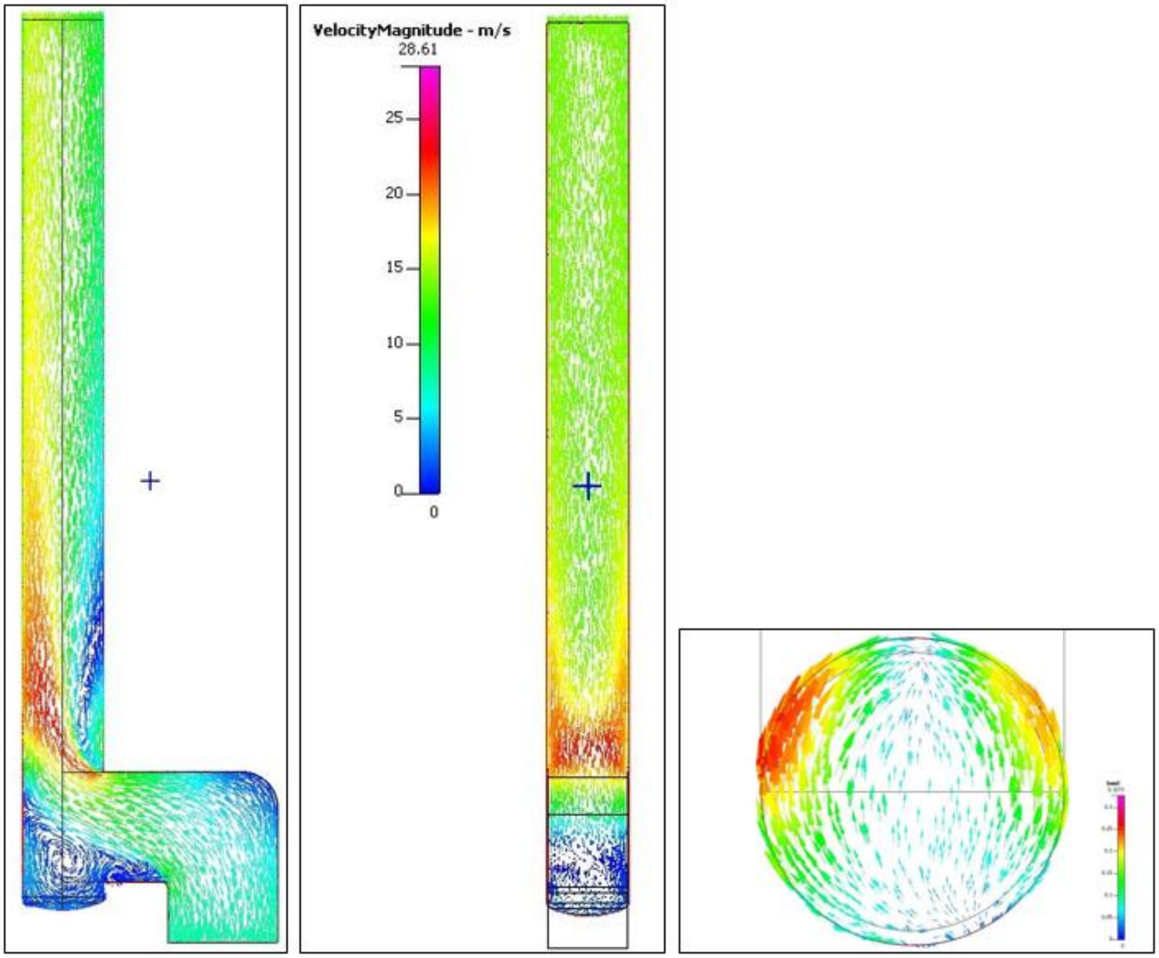


Figure 3 Computed velocity fields for a smokestack with two 90˚ flow direction changes, courtesy of Elisabeth Moore, NIST.

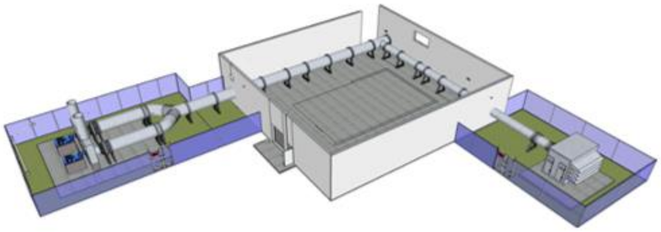
2.1.2. Results

In light of these measurement challenges, NIST is performing research to improve smokestack flow measurements in the three special measurement facilities shown in Figure 4.

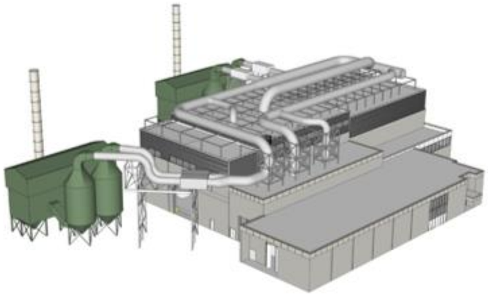
1) <u>The NIST Wind Tunnel and Air Speed Calibration Service:</u> The air speed service calibrates pitot probes as a function of (1) air speed from 5 m/s to 30 m/s, (2) pitch angle ±45°, (3) yaw angle ±180°, and (4) turbulence intensity from 0.1 % to 20 %. We have characterized the tilt response of the commonly used pitot probes (S-probe, prism probe, and spherical probe) as well as new probe shapes fabricated using 3D printers. Recent results show that using an S-probe and the recommended calibration factor of 0.84, leads to errors on the order of 5 % for moderate pitch angles (±10°). Non-nulling probes show great promise: they have 2 % accuracy and reduce the testing time necessary for a relative accuracy test audit (RATA) by a factor of 5 or more.

2) The NIST Smokestack Simulator: The Smokestack Simulator uses two variable speed blowers to produce velocities from 6 m/s to 26 m/s in a 1.2 m diameter test section with flow uncertainty of 0.7 % (95 % confidence level) and turbulence intensity level of 10 %. The Simulator was used to compare the results of standard pitot tube profiling methods to the facility's reference flow. It has also been used to test various time-of flight ultrasonic flow meter path configurations exposed to distorted velocity profiles, such as those in Figure 3. We found that the accuracy of continuous emission monitoring systems (CEMS) based on ultrasonic-flow-meter measurements can be greatly improved by using two, crossing ultrasonic paths. Using the Smokestack Simulator to test under conditions with significant swirl, two single path meters oriented 90˚ from each other differed from the flow reference by as much as 17 % when tested individually, but when the results from the two paths were averaged (a so-called X-pattern), the ultrasonic meter matched the flow reference within 1 %. A flow measurement technique developed by NIST called the long wavelength acoustic flow meter (LWAF) is under test in the Smokestack Simulator. In a 1/100th scale model stack, we have shown that a LWAF can measure the average velocity of a turbulent, swirling, wet, air flow with an uncertainty of less than 1 %.

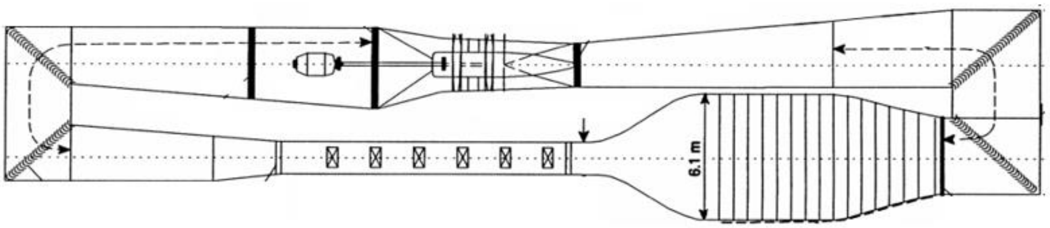
3) The National Fire Research Laboratory: The NFRL produces test fires under four large flow hoods that discharge flue gases through exhaust ducts equipped with flow and composition instrumentation and finally through a smokestack. It can produce fires as large as 20 MW using a well calibrated natural gas flow (0.2 %, at the 95 % confidence level). As such, the NFRL is well suited for comparing the pre- and post-combustion methods and for refining them. Recent CO_2 flux measurements conducted in the NFRL using the pre- and post-combustion methods agree within 7 %. Tracer gas dilution flow measurements (using SF_6 as the tracer gas) in the NFRL exhaust ducts confirmed uniform distribution of the tracer at the downstream sampling port and flow measurement repeatability of 1 % or less.



NIST Smokestack Simulator
(profiling methods, ultrasonic flow meters, velocity profile effects)



National Fire Research Laboratory
(pre- vs. post-combustion methods, tracer methods)



NIST Wind Tunnel and Air Speed Calibration Service
(performance of air speed sensors, tilt response)

Figure 4 NIST facilities used for research to improve smokestack flow measurements.

NIST is engaged in cooperative research with other organizations:

1) The Electric Power Research Institute (EPRI): a Cooperative Research and Development Agreement will enable field tests in the USA of recommended improvements to the flow RATA.
2) The National Institute of Metrology of China (NIM) and the Korea Research Institute of Standards and Science (KRISS): a strong, informal working arrangement will enable field tests in China and will facilitate international dissemination of good measurement practices.

2.1.3. Conclusions

Research to improve smokestack flow measurement continues, guided by our discussions with stakeholders at this workshop. Our goal is to produce a set of well-developed measurement methods that can serve as a toolbox for better smokestack flow measurements. Are non-nulling pitot probe RATA tests economical, time efficient, and more accurate than presently used methods? Can multipath ultrasonic flow meters reduce or eliminate the need for RATA tests? Can the long wave acoustic flow meter be applied in full scale smokestacks using ambient sound sources? What uncertainty can be achieved with tracer dilution methods?

3. Session 1 – Air Emissions Testing Bodies (AETB)

3.1. Accreditation of Air Emission Testing Bodies for GHG Measurements and Data Collection - Opening the Discussion

Presenter: Scott Swiggard – Golden Specialty Laboratory, Chris Gunning – American Association for Laboratory Accreditation (A2LA)

3.1.1. Introduction

In the early 1980s, fixed laboratories performing testing and calibration activities went through a change in process by implementing accreditation of laboratories and immediately began to see the benefits of this course of action. The source testing industry realized that their laboratories could benefit from this process as well and began to implement voluntary accreditation nine years ago. With over three hundred fifty (350) companies performing work gathering GHG data, only sixteen (16) companies are currently accredited demonstrating that there is still much progress to be made.

Laboratory accreditation is a formal recognition by an authoritative third party of the competence of a laboratory to perform specific tests. It is important to note that independent third-party involvement in assessing laboratory competence focuses on the requirements of ISO[1]/IEC[2] 17025; however, additional program requirements or alternate standards can be assessed as well. The source testing industry capitalizes on this flexibility by offering accreditation to ASTM[3] D7036 which is based on ISO/IEC 17025.

Benefits of Accreditation to the Laboratory:

- Accreditation by a third party provides credibility to the testing community and establishes a level playing field.
- The Accreditation Body’s involvement in the **conduct of assessments and the review of assessment outcomes creates and maintains consistency** between assessments.
- Accreditation by a third party allows access to **experienced, expert assessors who are technically competent in the fields assigned**.
- Use of Accreditation Bodies that are signatories to the ILAC (International Laboratory Accreditation Cooperation) Mutual Recognition Arrangement (MRA) provides a high level of confidence in the Accreditation Body’s competence. This confidence is based on the requirement for the Accreditation Body to undergo routine, rigorous peer evaluations against long-standing international standards for assessing quality as well as on the satisfaction of the laboratories themselves.

---

[1] International Organization for Standardization
[2] International Electrotechnical Commission
[3] American Society for Testing and Materials

Benefits of the laboratory accreditation to their clients and the impact to the quality of data were discussed.

3.1.2. Discussion

Under current rules there remain two potential management style options for the Source Testing Industry, Command and Control, and Process.

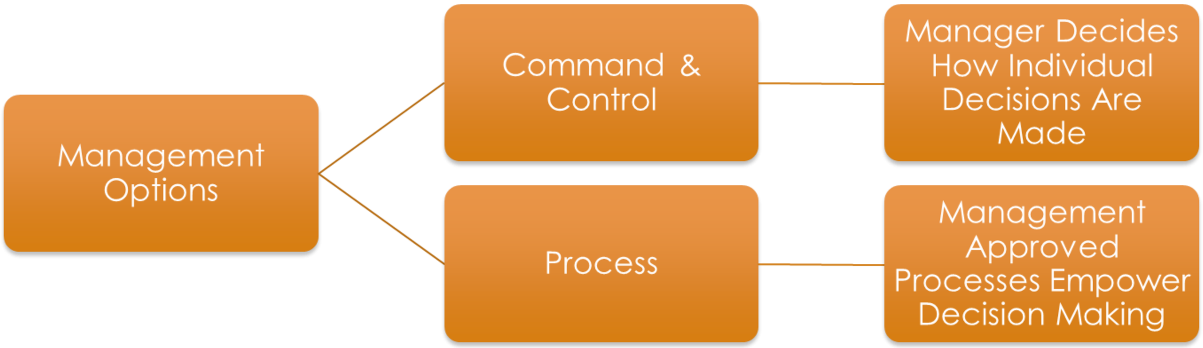


Figure 5 Organizations are managed in two ways

Both options lend themselves to the need for a third-party independent assessment which serves two important functions:

1) Verify structure: Verification that the required systems, if implemented, are in place to achieve conformance with a standard.
2) Verify function: Verification that the required systems are being implemented.

In short, assessments evaluate the structure and function of an organization's systems relative to the requirements of standards and the procedures that the organization establishes to conform to standards.

3.1.3. Summary

The current regulations allow for self-certification or attestation of compliance. Simply, "I follow the standards and we comply" from a company executive claim:

- The organization may not follow the standard and not know about it or have knowledge about it and no motivation to change.
- Assessing one's own work is difficult at best
- Internal assessors do not normally have adequate training on the standards or assessing techniques

There is significant value in Third Party accreditation and assessments:

- Independent assessment of compliance to standards and competence to perform specific tasks

- Assessors with adequate training and technical competence to perform an in-depth assessment

3.2. Overview of 2016 Updates to ASTM D7036, A Quality Management Standard for Emission Testing

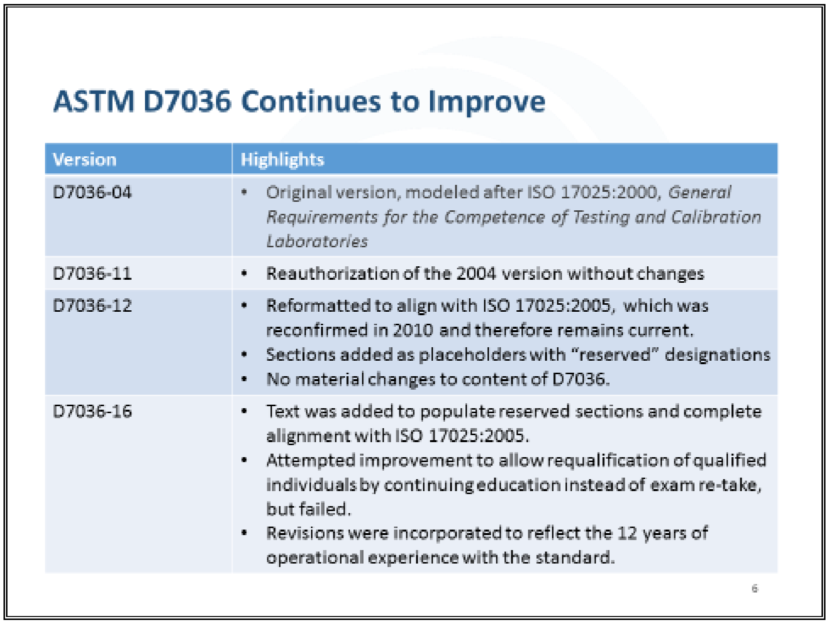
Presenter: David L. Elam, Jr. – TRC Companies

3.2.1. Background

In the preamble to the Minimum Competency Rule (MCR) [8], EPA reports problems with the quality of emission test data:

> “EPA believes the evidence is strong that unqualified, under-trained, and inexperienced testers are routinely deployed on testing projects.”
>
> “There are many reasons why voluntary compliance has not worked, including disagreement among test companies on a minimum competency standard, and the source’s often used practice of hiring the lowest bidder.”

The MCR seeks to improve emission testing data quality for Part 75 test programs by requiring source testers – Air Emission Testing Bodies (AETBs) – to conform to ASTM D7036-042 “Standard Practice for Competence of Air Emission Bodies.” ASTM D7036-04 is a consensus quality management standard based on ISO 17025:1999 “General requirements for the competence of testing and calibration laboratories.” Figure 6 outlines the history of the standard, which reflects improvements based on use of the standard. Although the standard continues to improve, the regulation requiring it has not been revised to reflect the current version of the standard.



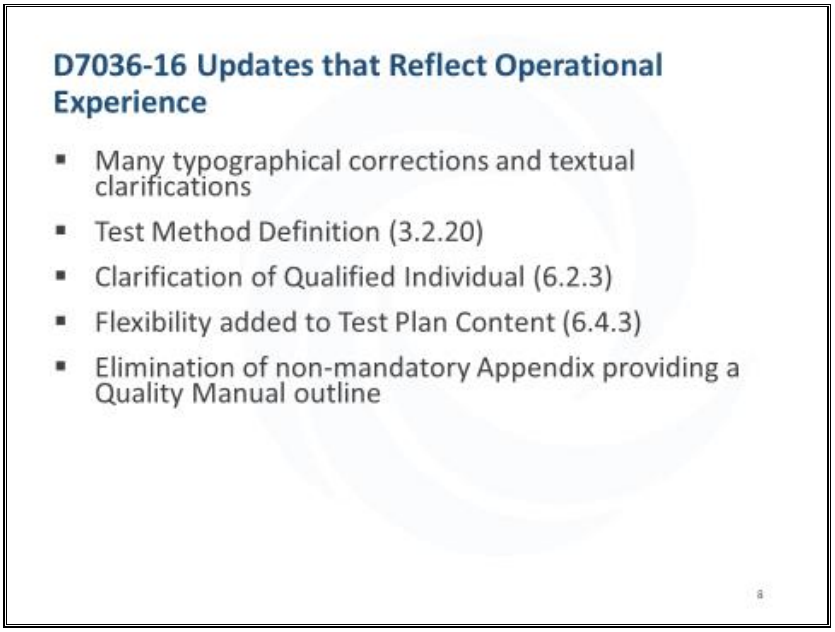
ASTM D7036 Continues to Improve

Version	Highlights
D7036-04	• Original version, modeled after ISO 17025:2000, *General Requirements for the Competence of Testing and Calibration Laboratories*
D7036-11	• Reauthorization of the 2004 version without changes
D7036-12	• Reformatted to align with ISO 17025:2005, which was reconfirmed in 2010 and therefore remains current. • Sections added as placeholders with “reserved” designations • No material changes to content of D7036.
D7036-16	• Text was added to populate reserved sections and complete alignment with ISO 17025:2005. • Attempted improvement to allow requalification of qualified individuals by continuing education instead of exam re-take, but failed. • Revisions were incorporated to reflect the 12 years of operational experience with the standard.

Figure 6 ASTM D7036 has been revised three times to reflect implementation experience with the standard.

3.2.2. Discussion

Federal regulations require that source testing firms must conform to ASTM D7036-04 when performing Part 75 emission testing projects. As the standard has been adopted and implemented, a number of problems have been identified by the AETBs, sources, and accreditation bodies. Although the 2011 and 2012 revisions did not materially change the standard, these revisions did lay the groundwork for the 2016 revisions, which reflected clarifying and meaningful changes to the standard. Figure 7 identifies the key revisions that appear in ASTM D7036-16. Because ASTM D7036-04 is cited in the MCR, it is the version that source testing firms must follow when performing Part 75 test programs.



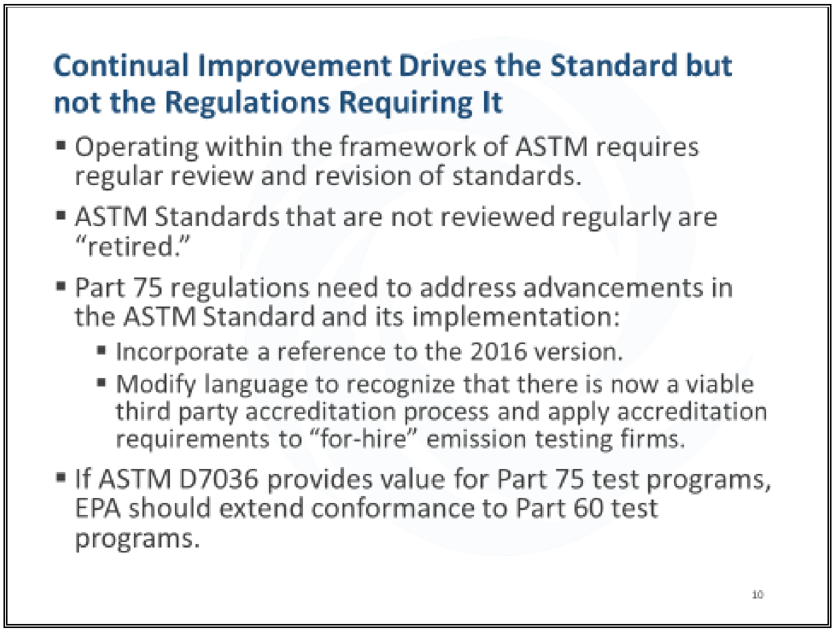
D7036-16 Updates that Reflect Operational Experience

- Many typographical corrections and textual clarifications
- Test Method Definition (3.2.20)
- Clarification of Qualified Individual (6.2.3)
- Flexibility added to Test Plan Content (6.4.3)
- Elimination of non-mandatory Appendix providing a Quality Manual outline

Figure 7 The 2016 revisions to ASTM D7036 improved the standard with clarifying information.

3.2.3. Summary

ASTM D7036 has been subjected to consensus-based continual improvement that reflects the operational experience of the source testing community. Unfortunately, the regulations requiring ASTM D7036 conformance have not been revised to reflect improvements in the standard. If EPA finds value in ASTM D7036, regulations requiring conformance to it should evolve with the standard as outlined in Figure 8.



Continual Improvement Drives the Standard but not the Regulations Requiring It

- Operating within the framework of ASTM requires regular review and revision of standards.
- ASTM Standards that are not reviewed regularly are "retired."
- Part 75 regulations need to address advancements in the ASTM Standard and its implementation:
  - Incorporate a reference to the 2016 version.
  - Modify language to recognize that there is now a viable third party accreditation process and apply accreditation requirements to "for-hire" emission testing firms.
- If ASTM D7036 provides value for Part 75 test programs, EPA should extend conformance to Part 60 test programs.

Figure 8 Part 75 regulations need to be revised to reflect improvements in the standard and its implementation.

3.3. Evaluation of Uncertainties in Velocity Probe Calibration Procedures

Presenter: Tom Martz – Electric Power Research Institute

3.3.1. Introduction

The Electric Power Research Institute (EPRI) is studying uncertainties in the use of Continuous Emission Monitoring System (CEMS) instrumentation for heat rate and CO_2 emission calculations. Previous work identified reference method volumetric flow rate measurements, which are used to audit and calibrate stack flow monitors, as a significant source of uncertainty in these calculations. A key objective this year was to continue defining and developing best practices for reducing uncertainty in reference method stack flow measurements. Areas of focus included an investigation of EPA Method 2F calibration procedures. Using this method, a large portion of flow measurement uncertainty may be tied to the calibration of three-dimensional (3D) velocity measurement probes. The potential benefits of more rigorous 3D probe calibrations, as compared to EPA Method 2F, were examined. An uncertainty calculation spreadsheet was developed to analyze the relative impact of the measured parameters which contribute to the overall Method 2F calibration uncertainty. Tasks also included an investigation of 3D velocity probe calibration sensitivities to Reynolds number, with testing performed by the National Institute of Standards and Technology (NIST). Prism and spherical probe head designs were tested in the study.

3.3.2. Results and Discussion

Method 2F provides generous allowances in terms of the required measurement accuracy and wind tunnel configuration. As an example, the left-hand column of Figure 9 illustrates the calibration uncertainty that would result if a wind tunnel facility simply used the maximum allowable accuracies for each of the transducers. Note that the method does not provide any specification or guidance regarding the range of the transducers to be used. The choice of range can have significant consequences on uncertainty, since the transducer accuracy specifications are provided in terms of full-scale (FS). A larger transducer range will introduce greater potential error in the measurement of interest. For the purposes of this example, a range of 0 to 5 inches of water column (IWC)[4] (0 to 1245 Pa), was selected for both the P1-P2 transducer and the calibrating transducer. A wind tunnel velocity of 27.4 m/s (90 ft/s) was assumed for this calculation. The resulting calibration uncertainty is 5.8 %, as indicated by the red arrow in Figure 9. This uncertainty can be significantly reduced to 1.3 % with improved transducer accuracies, as illustrated by the red arrow in Figure 10. For this configuration, the transducer accuracies have all been greatly improved (from 1 % FS to 0.25 % FS for P1-P2, P2-P3, and P4-P5, and from 0.5 % FS to 0.1 % FS for the pressure calibrating device). This level of instrument accuracy is readily available to a wind tunnel calibration facility without

---

[4] The EPA Method 2F protocol, discussed in this section, specifies the pressure head in the non- SI unit inches of water column (IWC) where 1 IWC = 249.0889 Pa. To enable the reader to compare the discussion in this section to the protocol in Method 2F express the differential pressure in IWC instead of the SI unit Pa.

excessive cost. Reducing the upper limit of the transducer range from 5 IWC to 2 IWC, along with the improved instrument accuracies, lowers the uncertainty to under 1 %.

Calibrator Range	5	IWC
Calibrator Accuracy	0.5	%FS
P1-P2 Range	5	IWC
P1-P2 Accuracy	1	%FS
P2-P3 Range	+/- 2.5	IWC
P2-P3 Accuracy	1	%FS
P4-P5 Range	+/- 2.5	IWC
P4-P5 Accuracy	1	%FS
Transducer calibration agreement	2	%FS

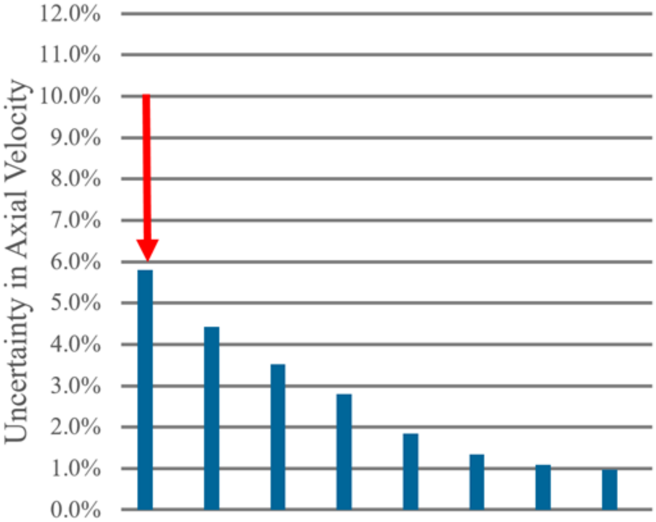


Figure 9 Example probe calibration uncertainty – maximum allowable accuracies.

Calibrator Range	5	IWC
Calibrator Accuracy	0.1	%FS
P1-P2 Range	5	IWC
P1-P2 Accuracy	0.25	%FS
P2-P3 Range	+/- 2.5	IWC
P2-P3 Accuracy	0.25	%FS
P4-P5 Range	+/- 2.5	IWC
P4-P5 Accuracy	0.25	%FS
Transducer calibration agreement	0.25	%FS

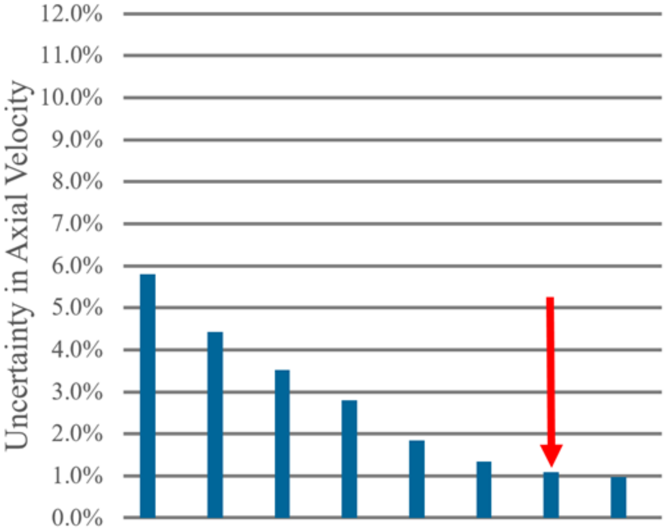


Figure 10 Example probe calibration uncertainty – with reduced maximum allowable accuracies.

3D velocity probes are known to be sensitive to velocity magnitude (Reynolds number). NIST calibrated a prism probe (provided by EPRI) at 6 different velocities. For an illustration of the effect of velocity on the F2 calibration curve, see Figure 11. There is 6 % difference in the prism F2 curves between 4.9 m/s (16 ft/s) and 29.9 m/s (98 ft/s) in the ±10˚ pitch angle range. Velocity-specific laboratory calibrations must be considered when performing reference method 3D flow measurements.

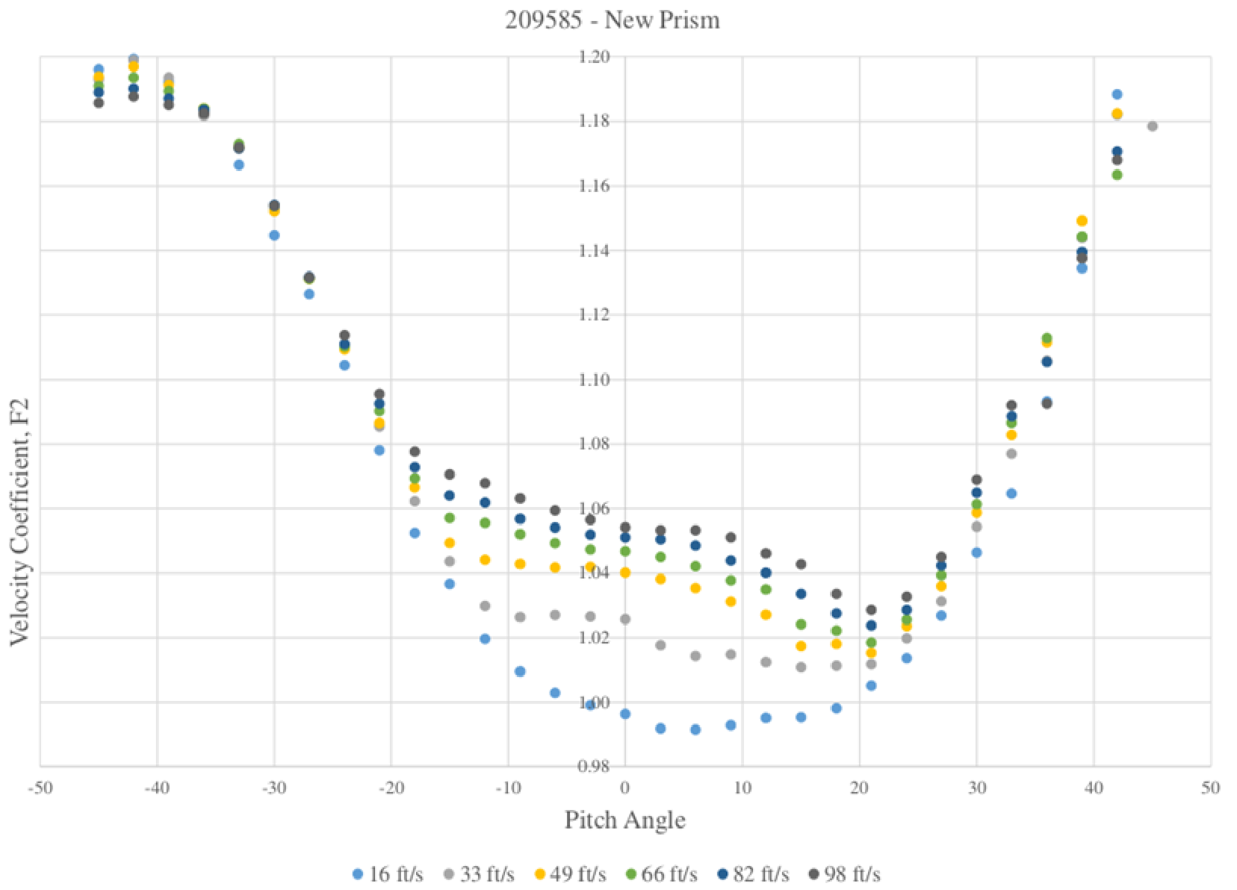


Figure 11 F2 curve; prism probe – 209585; multiple velocities

3.3.3. Summary

As part of the current EPRI study, the potential benefits of more rigorous calibrations of 3D probes, as compared to EPA Method 2F, were examined. An uncertainty calculation spreadsheet was developed to analyze the relative impact of the multiple measured parameters which contribute to the overall Method 2F calibration uncertainty. Several best practices, which go above and beyond Method 2F requirements, were identified. For example, use ±0.25 % of full scale (FS) accuracy (or better) instruments for P1-P2, P2-P3, and P4-P5. An accuracy of ±0.1 % FS (or better) is recommended for the pressure calibrator device. Use a transducer range such that readings are between 60 % and 90 % of full scale. Due to Reynolds number sensitivities, calibrate probes at velocity conditions as close as possible to the expected stack conditions.

3.4. Summary of Group Discussions

Facilitators: Rodney Bryant, Aaron Johnson, John Wright, Tamae Wong – NIST

The presentations from this session describe significant value in having an independent party assess the processes, competencies, and overall quality of an AETB to deliver reliable results. Unfortunately, only a handful of AETBs volunteer to participate in the full accreditation process. Self-accreditation or self-assessment by an AETB is allowed but may fall short of ensuring industry quality. The framework for accreditation programs currently exists in consensus standards organizations such as ASTM and ISO but conformance is not a requirement. An example was also presented of how an AETB can improve measurement accuracy by implementing best practices that exceed test method requirements. The example demonstrates that there is still room for the AETB industry to improve.

This section provides a summary, as interpreted by the editors, of responses from the group during the follow-up discussions to the previous presentations.

What type of proficiency measurements would be beneficial to the industry?
Measurements or studies that move the industry toward more normalized results of flow measurement were identified by the participants as being beneficial. Examples of such measurements or studies are round robin calibrations of flow sensors like the S-type pitot probe and full-scale proficiency testing of AETBs for flow RATAs at a certified stack. Standardization of the continuing education and testing of individuals was also identified as beneficial to the industry. The participants also suggested routine audits of field measurements by a third party to assess measurement quality and operations.

What are the measurement benefits of accreditation?
The majority of participants agreed that accreditation benefits AETBs by ensuring that companies can provide well defined practices and procedures for delivering accurate measurements, can defend the accuracy and traceability of their measurements, and can demonstrate consistency in their ability to deliver quality data. In addition, the participants agreed that accreditation benefits the industry by generating more consistency in overall emissions measurements, creating greater accountability for individual AETBs, and motivating the standardization of best practices and personnel training. Other benefits were better metrics for source owners to evaluate bids and better oversight to help fix or mitigate problems.

What are the hurdles preventing accreditation by more Stack Testing Companies?
Participants agreed that the initial cost and time required to achieve accreditation is the most significant hurdle preventing a company from becoming accredited. Furthermore, the subsequent cost and time required to maintain accreditation was also viewed as a hurdle. In

addition, the group agreed that unless accreditation is required, companies will not be motivated to invest the time and resources to become accredited. Other hurdles are the perception that it is just a paperwork exercise and a perceived lack of tangible evidence that accreditation has monetary value or provides a return on investment.

What is your view or your company's view of "Accreditation"?

Participant views were generally positive and supportive of accreditation. For example, many felt that accreditation will help ensure consistency across the industry and it will improve companies' individual performance, therefore leading to better products and greater client satisfaction. A suggestion worthy of attention was the creation of a central facility for training and competency testing of AETBs. Such a facility could support standardizing the accreditation process beyond the paperwork to the actual skills of the people implementing work. However, some skeptical views were shared by the group. For example: accreditation is not necessary while data from both accredited and non-accredited companies is accepted; and accreditation is difficult to justify due to the associated cost without evidence that it significantly improves the quality of the data.

What is the value of measurement uncertainty to the industry?

The participants agree that the value of quantifying measurement uncertainty is improved accuracy, quality, and consistency of data across the industry. It also helps to ensure emissions compliance with defensible data. The participants also agree that there is monetary value to measurement uncertainty, especially the uncertainty of flow measurements since flow is critical to all emissions measurements. For example, the lowest flow measurement can result in more credits or fewer emissions fees, while a failed flow RATA usually means extra cost for source owners. Other comments identified the value of quantifying measurement uncertainty as a tool for operations planning and decision making, improving processes, and innovating the industry.

4. Session 2 – Flow Measurements

4.1. Flow Measurement Uncertainty Using Tracer Gas Dilution Method

Presenter: Eric Harman – Colorado Engineering Experiment Station, Inc. (CEESI)

4.1.1. Introduction

How accurate is Tracer-Gas-Dilution (TGD) technology in measuring flowrates in smokestacks and flare gas piping? Some manufacturers and tracer gas dilution service providers claim uncertainties as low as 1 %. Is this achievable and can these claims be substantiated? This expanded abstract examines the underlining tracer gas dilution technology and presents tracer gas dilution data from blind laboratory testing conducted in a 25.4 cm (10 inch) pipe at CEESI.

4.1.2. Background

The gas flow measurement world is dominated by differential pressure meters and ultrasonic meters. To a lesser extent thermal mass meters, vortex shedders, turbine meters, Coriolis meters, and positive displacement meters are used to measure gas flow rates. While these technologies vary greatly they all have a physical presence in or on the pipe. For example, ultrasonic meters have acoustic transducers that reside in housings in openings in the pipe or in some cases are clamped onto the pipe externally. Unlike most other flow meters, Tracer-Gas-Dilution technology (TGD-technology) does not have a device in or on the pipe that directly or indirectly measures the gas flowrate. Rather, TGD-technology injects a known amount of tracer gas into the flow stream, draws a sample downstream, and measures the concentration of the tracer gas. By comparing the injected tracer gas flowrate to the downstream tracer gas concentration, the overall flowrate can be determined.

At some level, all flow meters are influenced by the velocity profile traveling down the pipe. In piping systems that have fittings (reducers, elbows, tees, bends, etc.) the velocity profile is distorted or skewed and can swirl radially. Distorted velocity profiles produce errors in the flow metering. Furthermore, smokestacks and flare gas piping often have very limited amounts of straight lengths of piping causing large uncertainties with most traditional flow meters. Velocity profile distortions can produce flow measurement errors as great as 25 % or even greater. These short-straight-run piping situations can force users to abandoned traditional flow meters, leaving them with few flow measurement alternatives. TGD-technology is one such alternative. Because TGD-technology does not directly measure the gas flow rate, it is very immune to velocity profile distortions. In fact, the more the flow stream is distorted, skewed, and swirled the greater the mixing between the tracer gas and the process gas. For this reason, TGD-technology provides a viable flow measurement alternative. TGD-technology is typically a one-time time measurement of the flowrate. Tracer gas injection and subsequent downstream gas sampling is rarely done on a continuous basis. During the injection and sampling period the process gas flowrate must be stable for TGD-technology to be accurate.

Figure 12 Tracer gas dilution installation

Testing Parameters

Fluid:	**Air**
Temp:	**70˚F (ambient)**
Pressure:	**12 psia (ambient)**
Velocity:	**1 to 150 ft/sec**
Pipe Size:	**10 inch pipe**
Pipe Orient:	**Horizontal**
Pipe Config:	**Ideal straight-run; Swirling flow after an elbow (both In-Plane & Out-of-Plane of elbow)**

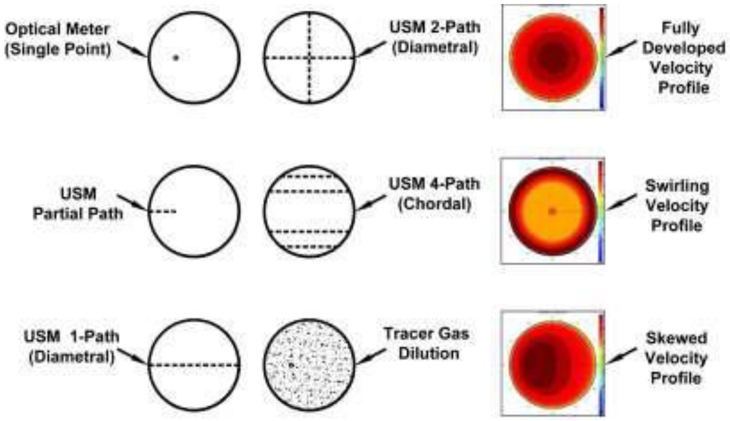


Figure 13 Tracer gas dilution method vs. other technologies

Consider How Different Flow Meters Sense Flow:

Smokestacks have large diameters and cannot afford a large pressure drop across a flow meter. For these reasons, full-bore flow meters like orifice-plates and Venturis cannot be used. Therefore, most smokestack flow meters only measure a small portion of the flow. Figure 13 shows how a USM (Ultrasonic Meter) (4-path Chordal), USM (2-path, Diametral), USM (1-path, Diametral), USM (1-path, Partial Insertion), Optical Flow Meter, and Tracer Gas Dilution Methodology sense flow. Fully developed, swirling and asymmetric (skewed) velocity profiles are shown on the right of Figure 13. From Figure 13, it can be seen that if properly applied, TGD-technology could sample the entire pipe diameter.

While chemical injection may be somewhat immune to velocity profiles, large random errors suggest this technology is sensitive to the multiple components inherent in its determination of flow rate. These components include an accurate measurement of the tracer gas flow rate via a thermal mass flow meter, dilution sensitivity, area under-the-curve peak integration for concentration analysis, complete chemical mixing, minimizing gas sampling errors, and minimizing background baseline "zero" influences.

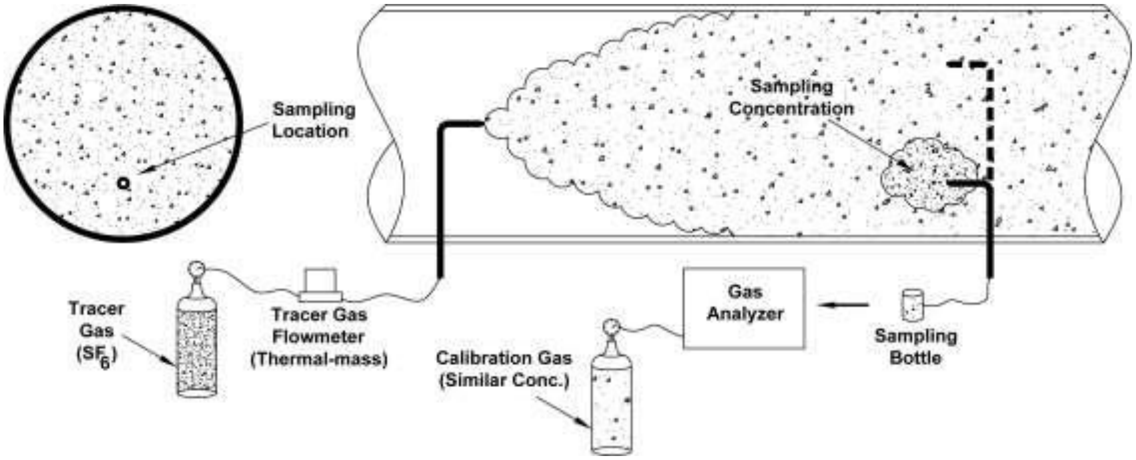


Figure 14 Individual components involved in tracer gas dilution technology

4.1.3. Results

TGD-Technology Test Results:

TGD-technology results are shown in Figure 15, and shows a ±6 % to ±10 % error between 0.305 m/s to 3.65 m/s (1 ft/s to 12 ft/s). To understand if these results are reasonable we need to consider all the individual components that go into the TGD-method, and calculate the overall uncertainty of the measurement.

TGD-Technology Equations:

From ASTM E2029 (Volumetric & Mass Flow Rate Measurement in a Duct Using Tracer Gas Dilution) the following equation is used to measure flow rate:

$$F_U = \frac{(C_I - C_D)}{(C_D - C_U)} F_I \qquad (1)$$

where:

F_U = Upstream mass flow rate

C_I = Injection stream concentration (mass) of tracer gas

C_D = Downstream concentration (mass) of tracer gas

C_U = Upstream concentration (mass) of tracer gas

F_I = Injection mass flow rate

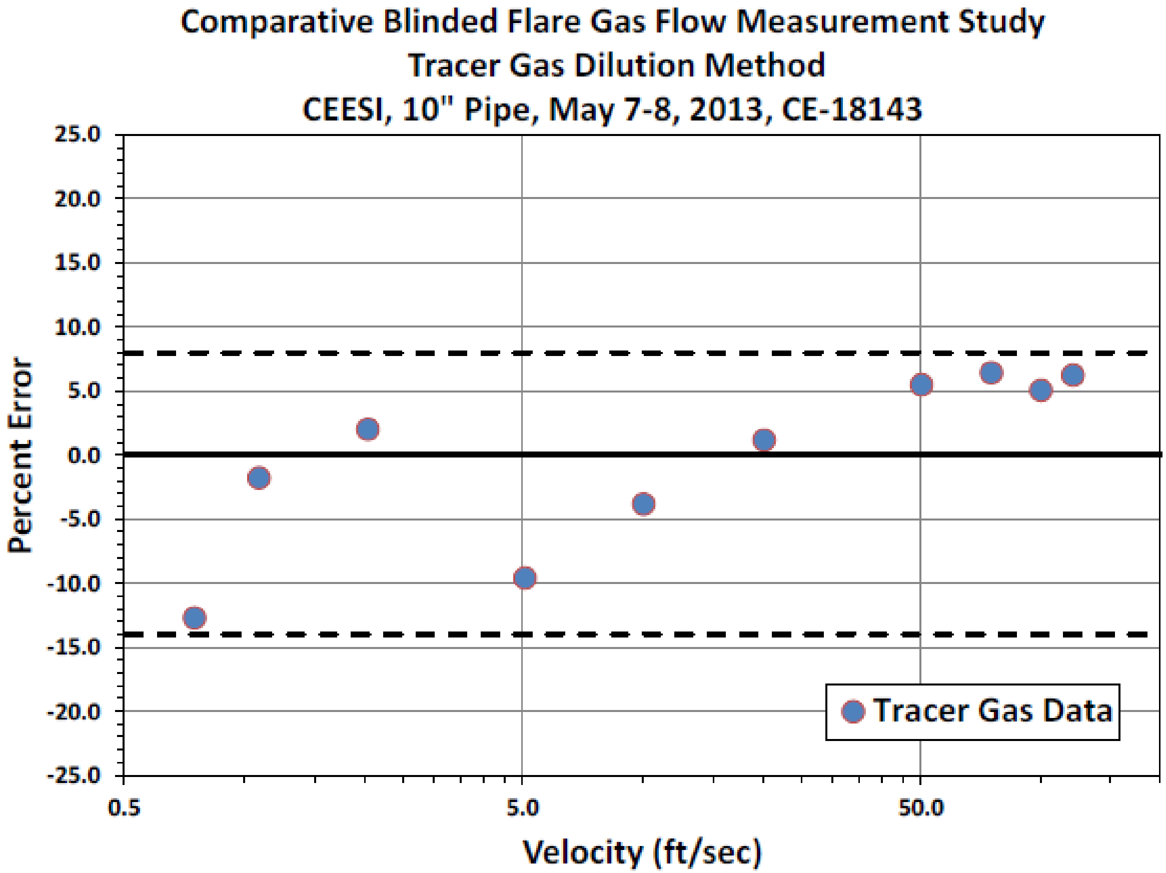


Figure 15 Tracer gas dilution method test results

Uncertainty Equations & Results:

The uncertainty in equation (1) can be written as:

$$\frac{u(F_U)}{F} = \sqrt{\left[\left(\frac{\Delta C_I}{C_I}\right)^2 + \left(\frac{\Delta F_I}{F_I}\right)^2 + \frac{(\Delta C_D)^2 + (\Delta C_U)^2}{(C_D - C_U)^2}\right] + 2\left[\frac{\sum_{i=1}^{N}(F_I^i - F_I)^2}{(N-1)F_I^2} + \frac{\sum_{i=1}^{N}(C_D^i - C_U^i - C_D + C_U)^2}{(N-1)(C_D - C_U)^2}\right]}$$

Applying the associated errors to each of the terms in the uncertainty equation above yields an overall calculated uncertainty:

$$\frac{u(F_U)}{F} = \sqrt{(0.04)^2 + (0.02)^2 + 2(0.05)^2} = \pm 0.083$$

From CEESI testing, Tracer Gas Dilution Method Uncertainty was ±6 % to ±10 %. This is reasonable because the ±6 % to ±10 % error observed from testing compares favorably to the calculated uncertainty of ±8.3 % at 68 % confidence level (or a coverage factor of $k = 1$).

4.1.4. Summary

Tracer Gas Dilution Observations & Comments:

- The worse the straight-run, the better the mixing.
- A large error due to the injection flow rate is possible.
- Consider the calibration gas uncertainty in the uncertainty calculations.
- Because concentration sampling is a discrete single point measurement, large random errors are likely, so many samples are required to reduce random error.
- How well the tracer gas mixes is hard to characterize.
- Tracer Gas Dilution is labor intensive (expensive) but may be a viable alternative when other methods are not possible.

4.2. Utility Stacks are Not Designed for Accurate Flow Measurement

Presenter: David Nuckols – Dominion Energy

Most existing utility stacks were built with little or no regard to measuring effluent flow accurately. Many stacks have poor flow profiles, such as stacks that serve multiple units, with varying flow profiles based on the varying load of the units feeding the stack. Some stack flow profiles will change based on operating conditions. This presentation will present CFD (computational fluid dynamics) model data of some of these flow measurement challenges.

4.3. Progress of NIM's Smokestack Simulator and Field Measurement in Power Plants

Presenter: Liang Zhang – National Institute of Metrology of China (NIM)

4.3.1. Introduction

China is the world's largest greenhouse gas (GHG) emitter; however, over the last decade China has been actively working toward reducing its carbon footprint. In 2013 the Chinese government disseminated GHG accounting methods and reporting guidelines to 10 industrial sectors. In 2017, China implemented a pilot carbon trading program like the cap and trade program initiated in the U.S. under the Acid Rain Program. [9] The Chinese pilot program for carbon trading initially included only 7 of its 23 provinces, but future plans include expansion to additional provinces.

Accurately measuring GHG emissions is an important step toward reducing China's carbon footprint. High fidelity GHG measurements will help ensure that China's mitigation efforts are progressing as planned. The National Institute of Metrology (NIM) is tasked to help assess and improve the accuracy of China's GHG accounting method, which is currently based on the fuel input calculation. An assessment of the fuel calculation method revealed significant errors, which are believed to be attributed to (at least in part) to inaccurate values of coal emission factors. [10] When the pilot program commenced, China did not have a well-established database to provide reliable emission factors for the types of coal used in China. As such, China used default emission factors from the Intergovernmental Panel on Climate Change (IPCC) database. [11] However, Liu et. al. found that the IPCC emission factors overpredict the carbon content of Chinese coal. [12] Consequently, China's current GHG accounting method is prone to errors, which have become one of the main problems in China's carbon trading market. China is seeking to gradually improve GHG measurement accuracy and thereby bolster its carbon trading market.

Direct measurement of CO_2 in exhaust flue gas can provide improved accuracy over the fuel calculation method, particularly when the carbon content varies significantly in the coal. Stack CO_2 emissions are determined by the product of the CO_2 concentration and the bulk flow. The concentration measurement is relatively well-established and its accuracy can be checked via calibrations that are traceable to certified gas standards. However, due to the huge size of stacks and the complex velocity flow field, accurate measurement of flue gas flowrate presents a great challenge. The adverse flow conditions in the stack make it necessary to calibrate the flue gas flow meter in the flow conditions that it will be used. The primary method for performing this in situ calibration is the S-probe relative accuracy test audit (RATA). However, the accuracy of the S-probe, like the flue gas flow meter, can be adversely affected by adverse flow conditions. To solve this problem, NIM initiated a research program to establish high accuracy measurement and calibration methods using computational models, experiments in simulated stack conditions, and full-scale field tests. The goal is to identify reliable measurement techniques that provide the desired accuracy at specified uncertainties.

4.3.2. Results and Discussion

NIM's Smokestack Simulator (SMSS) is a scale-model of real stacks and ducts. This system uses swirl generators to generate different swirls to simulate flow fields in real stacks and ducts. Using this system, NIM will test the performance of the existing flue gas flowmeters in complex flow fields, improve the flowmeters and its measurement methods. At the same time, the SMSS also has the function of a large diameter wind tunnel, which can be used to calibrate the field test standard flue gas flow meters at different pitch and yaw angles.

As shown in Figure 16, the SMSS uses a U-shape configuration. It consists of inlet nozzle, reference section, expanding turning section, a test section, and outlet variable frequency fan. The facility uses ambient air as the flow medium, and the maximum flowrate can reach 100000 m^3/h. The inlet nozzle and the reference section provide a traceable standard flowrate for the facility. The reference section uses DN800 circular pipe (*i.e.*, nominal diameter 800 mm). Since uniform axial velocity can be formed downstream of inlet nozzle, the reference section can also be used as a wind tunnel to calibrate pitot tubes. The velocity ranges from 0.2 m/s to 70 m/s. Because the facility uses a U-shape arrangement, an expanding turning section is used to reduce the impact of turning on the flow field. The size of the test section can be modified using either of two circular pipelines consisting of a DN1000 (1000 mm) and a DN700 (700 mm). In addition, a 0.7 m by 1 m rectangular section can be installed in the test section. Thus, we can simulate a vertical circular stack and a horizontal rectangular duct, respectively. The two differently sized circular pipes will be used to study the scale effect of the flowmeters. The velocity range of test section ranges from 0.5 m/s to 30 m/s. In the test section, we use replaceable swirl generators to generate the complex flow patterns typical of real stacks and ducts. The traceable flow measurement made in the reference section is used to assess the performance of the flue gas flowmeter in smokestack-like flow conditions. The flowrate of the whole facility is controlled by two variable frequency fans. The inlet nozzle, reference section, test section, and the outlet fan are all mounted on a sliding track and can slide along the axial direction.

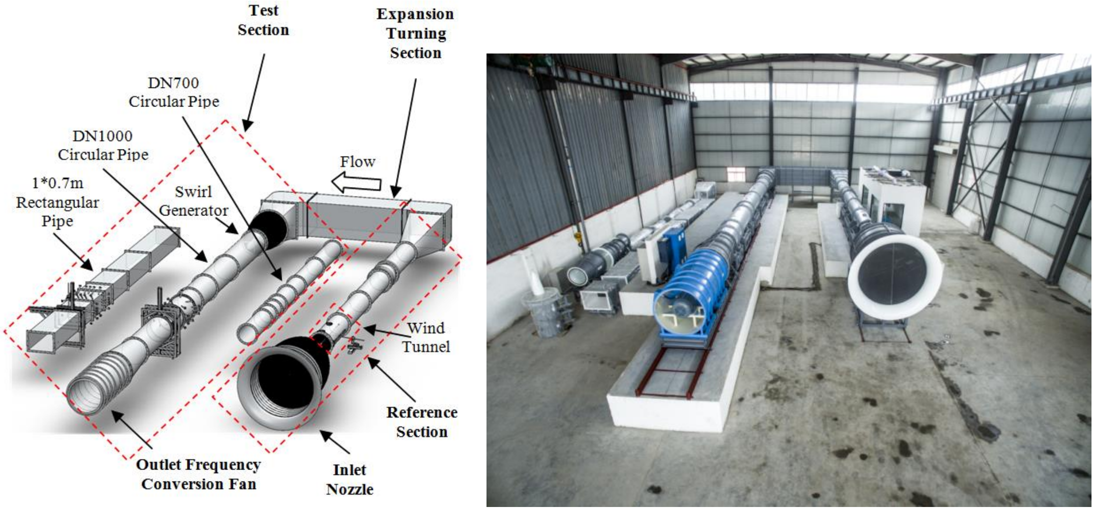


Figure 16 SMSS components.

In order to verify the accuracy of results found in the SMSS, we will perform field tests in industrial scale stacks and ducts at a coal-fired power plant and a natural gas power plant located in Henan Province of China. Figure 17A shows the natural gas power plant stack. The inner diameter of the stack is 6.9 m. As shown in the figure a 6-path ultrasonic flow meter (USM) is installed near the top of the stack using the top two platforms and the pitot traverse sampling method (or RATA) is performed near middle of the stack on the lower platform. The 6-path USM uses the Optimal Weighted Integration for Circular Sections (OWICS) [13] integration method to determine the flow. The coal-fired power plant is shown in Figure 17B. In contrast to many U.S. stacks, the flue gas is measured in a rectangular duct (4.1 m wide and 8.1 m high) upstream of the exhaust stack. We are building 3 platforms on both sides of the horizontal duct to use for the flow measurement test. The RATA testing with the pitot tubes will be located upstream of the 6-path USM. We plan to validate field results by comparing flow measurements from the flue gas flow meters with RATA results for both conventional probes (*i.e.*, the S-probe) and 3-dimensional probes (*i.e.*, prism and spherical probes). In the natural gas power plant, we will also compare CO_2 flux measurements made in the stack (*i.e.*, the direct measurement) versus the fuel calculation method. Good agreement between these two methods would help validate the accuracy of the stack flow measurement methods.

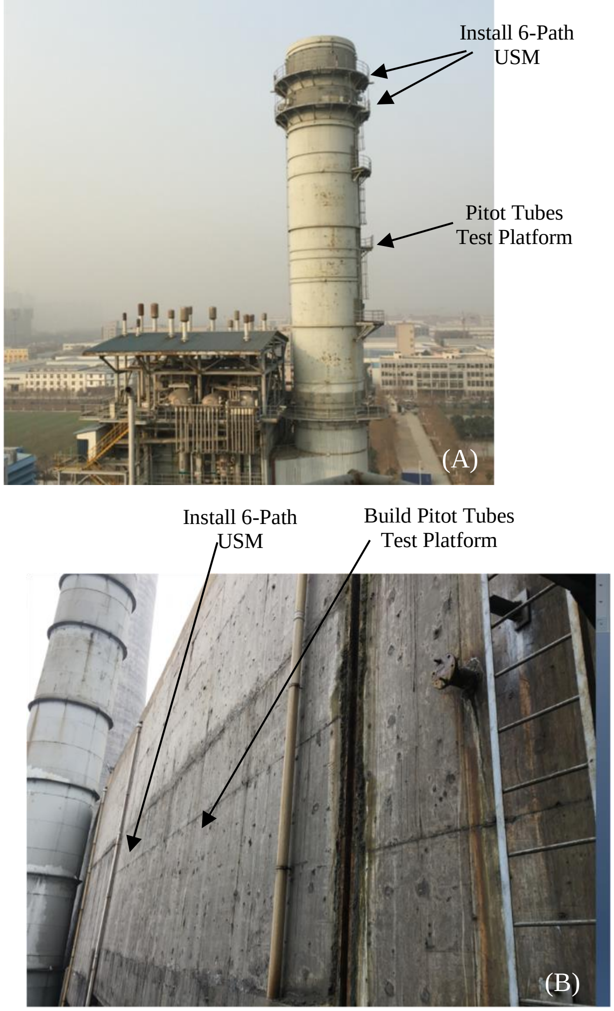


Figure 17 Flowmeter installation locations at power plants.

4.3.3. Summary

The National Institute of Metrology of China is carrying out research to improve GHG measurement accuracy from point sources such as power plant smokestacks. Better measurements are needed to support the development of China's carbon trading market. NIM's research is focused on identifying methods to accurately measure the flue gas flow rate both in stacks and in the ducts upstream of exhaust stacks. The size and complexity of the flow patterns in the stacks and ducts make accurate flow measurements difficult. NIM's approach to this problem has 3 tiers: 1) We built a Scale-Model Smokestack Simulator that generates the complex flow fields present in stacks in either circular test sections (DN700 or DN1000) or in a rectangular test section (0.7 m by 1 m), but can be accurately measured using an SI-traceable reference method; 2) We have implemented computational fluid dynamic (CFD) simulations to compare with SMSS measurements and provide useful insight on industrial scale stacks (CFD could help assess the optimum locations to perform the pitot traverse or the best location to install a USM); 3) We are preparing for field test in a coal-fired power plant and a natural gas power plant, with plans to install a 6-path USM in both power plants and compare the performance of USMs and various pitot probes.

4.4. Experimental Investigation on Geometric Parameters of S-Type Pitot Tube for Greenhouse Gas Emission Monitoring

Presenter: Woong Kang – Korea Research Institute of Standards and Science (KRISS)

4.4.1. Introduction

In greenhouse gas emission monitoring from industrial smokestacks in South Korea, the most common device used to measure stack gas velocity is the S-type pitot tube. Once installed in the stack this probe determines the volumetric flow rate continuously or makes a Continuous Emission Measurement (CEM). The geometric parameters of S-type pitot tube such as an external diameter, the distance between impact and wake orifices and the bending angle of orifices are described in several international documents including the ISO, ASTM and the EPA. Figure 18 shows some of the important geometric specifications designated in the standards. Various geometries of S-type pitot tube can affect the characteristics of S-type pitot tube coefficients including the sensitivity to velocity change, and the pitch and yaw angle misalignment. However, there is no detailed guidelines of S-type pitot tube geometry considering the accurate and reliable measuring characteristics in the international standards.

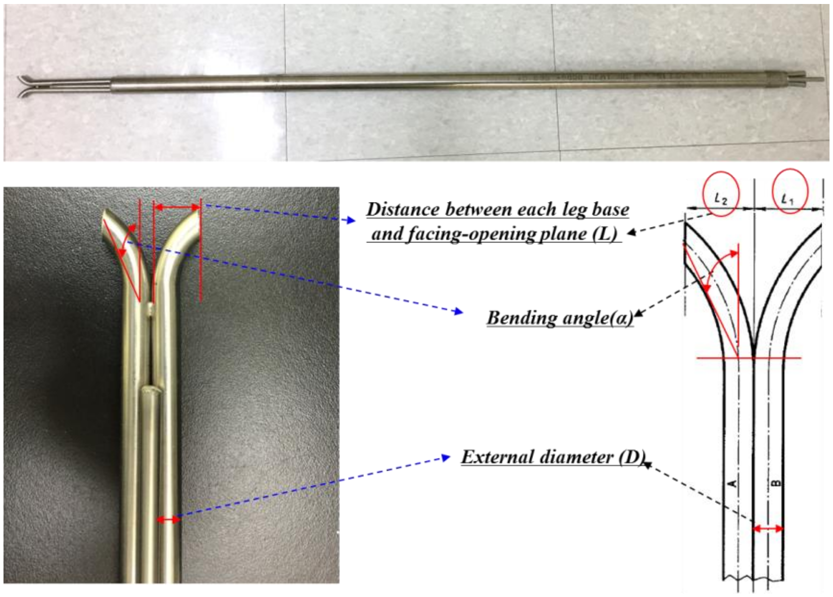


Figure 18 Configuration and geometric parameter of S-type pitot tube in the international documents

4.4.2. Results and Discussion

S-type pitot tubes with various geometric parameters, in this case the distance (L) between impact and wake orifices and the bending angle (α) of orifices were manufactured by a 3D printer. Wind tunnel experiments were conducted in Korea Research Institute of Standards and Science air speed standard system to determine the effect of geometric parameters on S-type pitot tube coefficients with the change of velocity, yaw and pitch angle. Particle Image

Velocimetry (PIV) was also used to understand flow phenomena around S-type pitot tube under various geometric and misalignment conditions by quantitative visualization, as shown Figure 19.

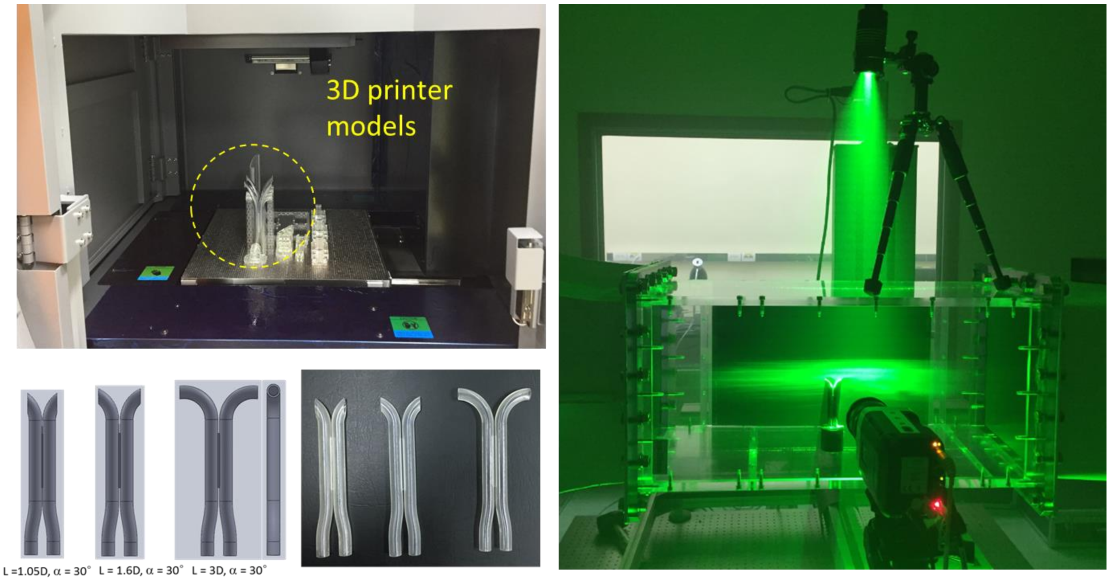


Figure 19 S-type pitot tubes by 3D printer (left). PIV experimental set-up for visualization around S-type pitot tube (right).

The results indicate that S-type pitot tubes with L=1.6D, α =30˚, shows the good linearity of Cp distribution from 2 m/s to 15 m/s due to less interference between impact and wake orifice of S-type pitot tube, as shown in Figure 20.

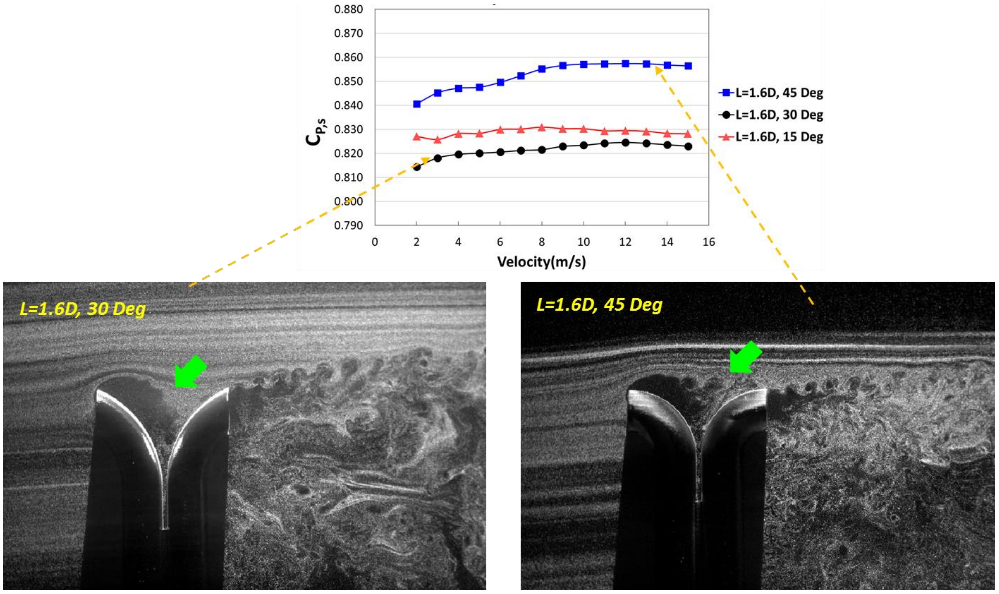


Figure 20 Flow visualization by PIV for understanding Cp distribution of S-type pitot tube

S-type pitot tube coefficients for L=1.6D, α =30˚ change by approximately 5 % as yaw angles change within ±35˚ while other models show up to 15 % change in yaw angle misalignment. S-type pitot tube with long distance (L) between two orifices, in the case of L=3D, is insensitive to pitch and yaw angle misalignments. However, the geometry with long distance is impractical for installation at the port of actual smokestacks.

4.4.3. Summary

S-type pitot tube is mainly applied to measure stack velocity for industrial smokestacks in South Korea. There are no detailed guidelines of S-type pitot tube geometry considering the accurate and reliable measuring characteristics in the international standards. Various geometric parameters on S-type pitot tube coefficients with yaw and pitch misalignment were investigated by 3D printing and wind tunnel experiments with PIV. The results indicate that S-type pitot tubes with long distance (L) between two orifices are insensitive to yaw angle misalignments. Their S-type pitot tube coefficients change by approximately 5 % as yaw angles change within ±35˚. The S-type pitot tube with bending angle (α) of 30˚ has a stability coefficient distribution under the change of velocity, yaw and pitch angle. However, in order to suggest the ideal geometry of S-type pitot tube in the smokestack, additional research is needed.

4.5. A Comparative Blinded Study of Different Flow Metering Technologies Used in Flare Gas and Stack Gas Measurement

Presenter: Eric Harman – Colorado Engineering Experiment Station, Inc. (CEESI)

4.5.1. Introduction

To better understand the capabilities of various flow measurement technologies in flare gas applications, six different flow meters were tested at CEESI. The different technologies included:

- 4-path Chordal Ultrasonic Meter (USM) Technology
- Two-path Ultrasonic Meter Technology (Diametral)
- Single-path Diametral Ultrasonic Meter Technology
- Single-path Partial Insertion Ultrasonic Meter Technology
- Tracer (Chemical) Gas Injection
- Optical Flow Meter Technology

The purpose of the testing was to compare different technologies in similar test conditions to determine which technology performs better. Secondly to evaluate each meter's performance in ideal straight pipe conditions and non-ideal pipe conditions after a single elbow in-plane and a single elbow out-of-plane. Each meter's performance was evaluated over typical flare gas velocity ranges.

Comparative Blind Study Parameters

Fluid:	Air
Temperature:	21.1° C (70˚ F) ambient
Pressure:	82.74 kPa (12 psia) ambient
Velocity:	0.305 m/s to 45.72 m/s (1 ft/s to 150 ft/s)
Pipe Size:	254 mm (10 inch) pipe
Pipe Orientation:	Horizontal
Pipe Configuration:	Ideal straight-run; Swirling flow after an elbow (both In-Plane & Out-of-Plane of elbow)

Figure 21 CEESI test facility and test piping

4.5.2. Background

Consider Flare Gas & Smokestack Velocity Profiles:

Figure 22 shows examples of a fully developed turbulent flow profile, a swirling profile and an asymmetric profile. Flare gas pipes and smokestacks typically have swirling and asymmetric velocity profiles. Most flow meters can perform well in a developed turbulent flow profile, but their uncertainty degrades significantly when swirling or asymmetric flows are present.

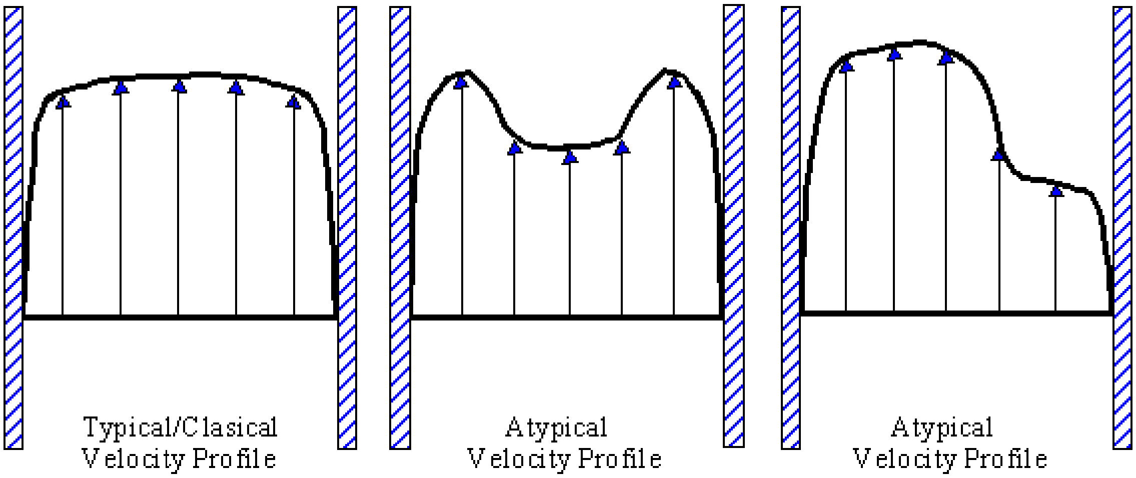


Figure 22 Examples of a developed turbulent flow profile, a swirling profile, and an asymmetric flow profile

Consider How Different Flow Meters Sense Flow:

Smokestacks have large diameters and cannot afford a large pressure drop across a flow meter. For these reasons, full-bore flow meters like orifice-plates and venturis cannot be used. Therefore, most smokestack flow meters only measure a small portion of the flow. Figure 23 shows how a USM (4-path Chordal), USM (2-path, Diametral), USM (1-path, Diametral), USM (1-path, Partial Insertion), Optical Flow Meter, and Tracer Gas Dilution Methodology sense flow. Fully developed, swirling and asymmetric (skewed) velocity profiles are shown in right of Figure 23.

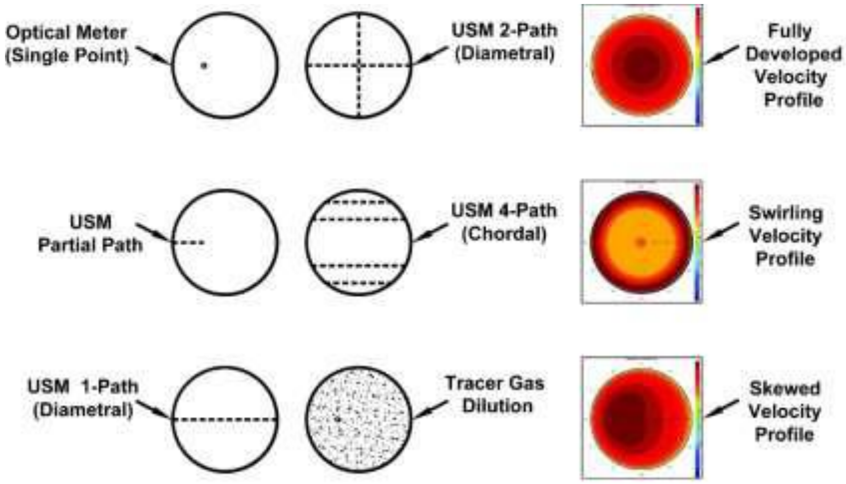


Figure 23 USM (4-path chordal), USM (2-path, diametral), USM (1-path, diametral), USM (1-path, partial insertion), optical flow meter, and tracer gas dilution methodology

4.5.3. Results

The meter performances are ranked below with one being the best and six being the worst:

1) USM (4-path Chordal)
   - Straight: ±1 %
   - Elbow: ±2 %
2) USM (2-path, Diametral)
   - Straight: ±5 %
   - Elbow: ±10 %
3) Tracer Gas Dilution
   - All Installations: ±6 % to ±10%
4) USM (1-path, Diametral)
   - Straight: ±3 % to ±7 %
   - Elbow: ±25 %
5) USM (1-path, Partial Insert.)
   - Straight: ±3 % to ±7 %: 0.914 m/s to 45.72 m/s (3 ft/s to 150 ft/s)
   - Straight: ±7 % to ±22 %: 0.305 to 0.914 m/s (1 ft/s to 3 ft/s)
   - Elbow: ±20 %
6) Optical Flow Meter
   - Straight: ±35 %
   - Elbow: ±35 %

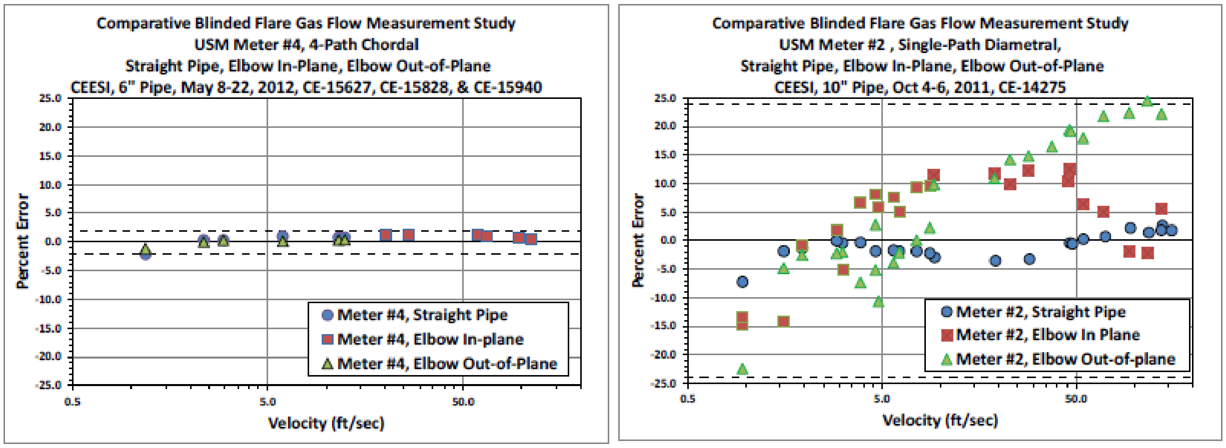


Figure 24 Results of 4-path chordal USM and single-path diametral USM

4.5.4. Conclusions

Based on the testing performed the following conclusions are made:

- The Chordal 4-Path USM performed the best.
- The 2-Path Diametral USM performed better than 1-Path Diametral USM.
- Diametral USM’s struggle in non-straight pipe configurations.
- Optical Meters not a viable meter for flare gas measurement.
- Tracer Gas Dilution Methodology is a viable solution when there is no straight pipe.
- For USM’s, the more non-diametral paths the more accurate the flow measurement.

4.6. Multipath Ultrasonic Configuration and When to Use Them

Presenter: Salvator Vigil – Teledyne

Emission stack meter accuracy expectations using ultrasonic transit time technology is difficult to establish and maintain since these meters rely on characterization to a specific flow profile to generate accurate, repeatable results. Influence factors on the flow profile, and the metering system used to characterize it, must be considered. These influence and meter system factors can be summarized as follows: Transit time path location & orientation; Number of sampling paths; Non-uniform fluid flow: Pulsation, Swirl Asymmetry.

Discussion will focus on the nature of these factors and an anecdotal estimate of their weighted effect on measurement uncertainty for transit time metering technology. Militating strategies for reducing these factors' effect(s) on meter uncertainty will be suggested, with the aim of stimulating further study into the efficacy of those strategies. A single fluid case will be used to simplify the discussion and is based on the products of combustion of natural gas (i.e., CO_2).

4.7. Summary of Group Discussions

Facilitators: John Wright, Rodney Bryant, Aaron Johnson, Tamae Wong – NIST

The presenters in Session 2 on Flow Measurements surveyed the state of the art and the significant challenges to obtaining low-uncertainty flow measurements for power plant smokestacks. They described sensor design and research programs aiming to reduce stack flow uncertainty. The speakers presented the results of laboratory scale projects that quantified measurement errors for the most commonly used flow measurement approaches: ultrasonic flow meters, velocity profiling using pitot tubes, and the tracer dilution method. While these methods can produce flow with uncertainty as low as 1 % under ideal conditions, in realistic conditions errors of more than 10 % are common. The challenges posed by real stack conditions include distorted velocity profiles, swirling flow, the tilt response of velocity sensors, and flow profiles that differ dramatically depending upon which units are in operation.

This section provides a summary, as interpreted by the editors, of responses from the group during the follow-up discussions to the previous presentations.

What are the flow measurement limitations in the field?
The most common response to this question was the stack geometry and the resulting impact on the velocity profile. More specific descriptions of the problem, include:

- Stacks often serve multiple generating units that are connected to the stack by a manifold. The velocity profile in the stack depends upon which of the units are operating and effects the RATA and CEMS measurements.
- It is difficult to obtain accurate stack dimensions and therefore to accurately characterize stack geometry.
- The velocity profile is far from ideal resulting in asymmetry and non-axial flow. Meandering profiles that change over time are also possible.

Other responses described the difficulties with measurement access the stack such as the number of access ports, the location of access ports and structural interferences preventing proper clearance for probes, as well as large diameter stacks requiring long probe lengths that can lead to excess probe sag and changes in probe alignment.

Participants also thought that human errors such as personnel skill and attention to the detail of probe positioning and reading the right numbers are an area of concern. Participants noted that instrumentation errors due to calibration inconsistencies, equipment condition, or low accuracy instrumentation are also a concern.

Should pitot probes be made traceable to NIST via calibration or some other means?
Most participants agreed that traceability to NIST is beneficial, but implementation will be hindered unless it is “not cost prohibitive”, necessary to meet “quality objectives”, or required by a “regulatory driver.” A few thought that a standardized geometry for the pitot probe is sufficient to achieve the desired velocity measurement uncertainty.

Is it conceivable to use multipath ultrasonic CEMS flow monitors as the benchmark for accuracy? That is multipath CEMS would replace RATA.
Most participants did not think that multipath ultrasonic flow monitors would replace RATAs for reasons such as flow monitors need to be verified on a routine basis, ultrasonic flow monitors are expensive, and their accuracy may depend on the flow distribution. Others thought that with the characterization and demonstration of repeatability in laboratory and field conditions, multipath ultrasonics can provide more repeatable and accurate measurements but the need for RATAs may never go away.

How do power plants use the heat input monitoring data?
The consensus was that heat input data are used to calculate the mass pollutants emitted or to measure operating efficiency. One participant responded that the data are used to assess CEMS system health.

What measurements do power plants use most often to optimize operations?
The most common responses for measurements to optimize operations were carbon monoxide (CO), sulfur dioxide (SO_2), or nitric oxides (NOX) emissions. CEMS flow, steam flow, or fuel flow measurements were also among the responses.

5. Session 3 – NIST Research Facilities

5.1. The National Fire Research Laboratory and Recent Results Supporting Smokestack Emissions Measurements

Presenter: Rodney Bryant – NIST

5.1.1. Introduction

The National Fire Research Laboratory (NFRL) is a research facility for the study of large-scale fire-structure interactions. It utilizes large flue gas hoods to capture the plume of fires as large as 20 MW. The exhaust ducts that service these hoods have a flow capacity of 5100 m^3 of air per minute. The NFRL is analogous to a stationary source and has the shared problem of accurate measurement of the flow and concentration of flue gas. While the stationary source must measure flow and concentration for emissions compliance, the NFRL performs the measurements to characterize the energy released from the fire experiments. The project objective is to demonstrate ±1 % measurement uncertainty for CO_2 emissions using the NFRL and, based on the lessons learned during the process, generate best practice guidelines for the industry to follow.

Figure 25 Photographic comparison of the NFRL (left) and a fossil-fuel-burning power plant or stationary source (right). Measurement locations for flue gas flow and gas species concentration are identified by the red circles.

5.1.2. Results and Discussion

The heat (or energy) released by a fire is the primary measurement of the NFRL. The measurement is conducted using oxygen consumption calorimetry. Detailed uncertainty audits of large-scale calorimetry measurements have all identified the flow measurement as a major source of uncertainty; contributing as much as 90 % to overall measurement uncertainty. Over time, flow measurements in the NFRL exhaust ducts have improved with added flow conditioning, characterization of the flow distribution using flow RATAs [14], and implementation of better flow monitors. The tracer gas dilution method (TGDM) was recently added as an independent confirmation measurement for the facility's routine flow measurement, averaging pitot-tubes on orthogonal chords. Recent experiments demonstrated an average difference of approximately 4 % or less between the two flow measurements. [15] The relative difference is within the uncertainty limits of the two methods, providing confirmation of the flow.

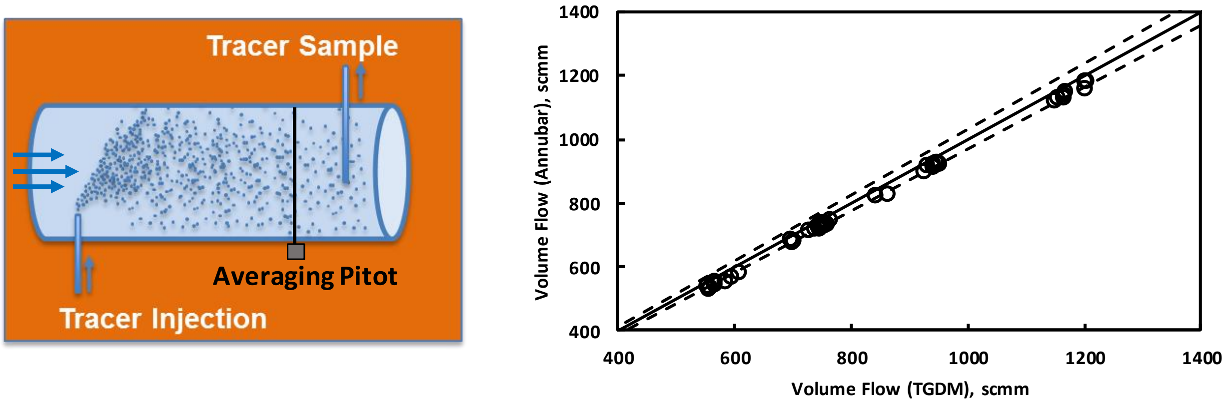


Figure 26 Conceptual schematic of TGDM (left). Comparison of volume flow determined by the TGDM and NFRL's routine flow measurement, the averaging pitot-tubes (right).

Large natural gas burners, capable of simulating fires as large as 20 MW give the NFRL the capability to generate up to 1100 g/s of CO_2. Precise amounts of heat energy and CO_2 emissions are computed from fuel flow and natural gas composition measurements upstream of the burners. [16] Energy and mass balance experiments, comparing exhaust duct measurements of heat release and CO_2 emissions to like measurements based on fuel input, have been conducted in the NFRL. Recent results from CO_2 mass balance experiments demonstrate an average difference of 2 % or less when comparing CO_2 emissions derived from exhaust duct measurements to those derived from fuel input measurements. The mass balance experiments not only provide independent confirmation measurements of CO_2 emissions, but they also provide evidence of accurate flow measurements in NFRL’s exhaust ducts.

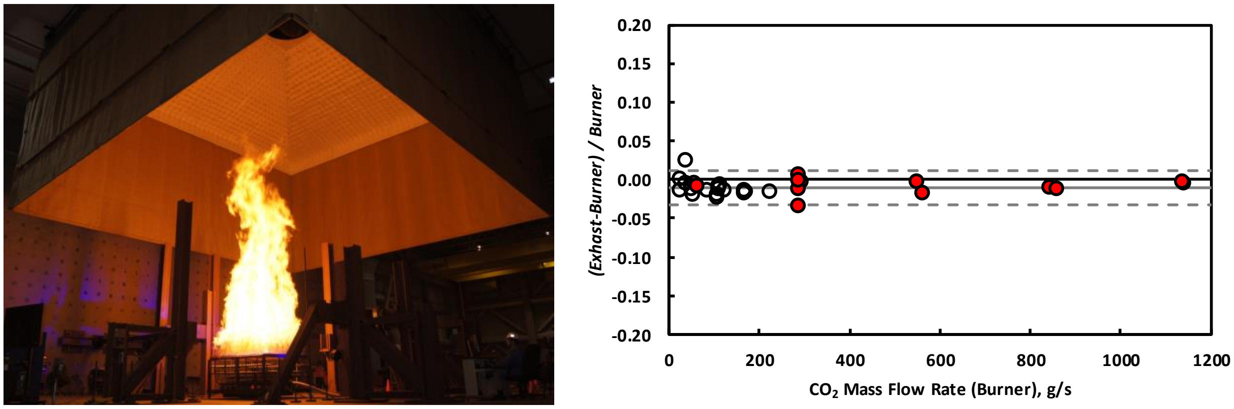


Figure 27 NFRL's 20 MW natural gas burner (left). Comparison of CO_2 emissions based on fuel input (burner) measurements and exhaust duct measurements (right).

5.1.3. Summary

The National Fire Research Laboratory is a large-scale research facility for the study of fire. It is analogous to a stationary source, such as an electric power plant. Like a stationary source, the NFRL has the same technical challenge of accurately measuring flow and gas species concentration in the flue gas. Continuous focus on improving NFRL’s flow measurement in its exhaust ducts has resulted in better accuracy for the facility’s flow measurements. The introduction of independent measurement techniques, like the TGDM, has provided tools to begin to evaluate the accuracy of large-scale flow measurements. These improvements have resulted in better agreement for the facility’s energy and mass balance experiments; providing evidence that accurate emissions measurements require accurate flow measurements.

5.2. The NIST Smokestack Simulator and Recent Results

Presenter: Aaron Johnson and Iosif Shinder – NIST

5.2.1. Introduction

NIST designed and built the Scale-Model Smokestack Simulator (SMSS) shown in Figure 28 to 1) to assess the flow measurement accuracy of the Relative Accuracy Test Audit (RATA), 2) to quantify the performance of Continuous Emissions Measurement Systems (CEMS) flow monitors, and 3) to use as a testbed to develop new stack flow measurement capabilities. Air is used as a surrogate for flue gas both for simplicity and because stack flow measurements depend primarily on the characteristics of the velocity field, and not on gas composition. For this reason, we replicate the complex velocity fields (i.e., turbulent, swirling flow, with an asymmetric velocity profile) inherent to industrial scale stacks in the facility's 1.2 m test section. The range of flow velocities is also commensurate to an industrial scale power plant, ranging from 6 m/s to 26 m/s (20 ft/s to 85 ft/s). The unique feature of the SMSS is that the test section flow velocity (V_{NIST}) is traceable to NIST's primary flow standards and known to better than ±0.7 %. In this way, the facility provides an absolute accuracy of stack flow measurements, in contrast to the relative accuracy provided by the flow RATA.

Figure 28. Photograph of the Scale-Model Smokestack Simulator (SMSS) showing the piping sections where air enters and exits the facility. RATA and CEMS performance evaluation are performed inside the building in its 1.2 m test section.

The schematic shown in Figure 29 highlights the functional design of the SMSS facility. Quiescent air is drawn into the air intake unit by engaging the fans at the facility exit. Cross-flow velocity components are damped as air moves through the intake unit. Low-speed air exiting the intake unit accelerates through the cone in Figure 28 and establishes a low-swirl and a nearly uniform velocity profile in the Reference Section. With the velocity field practically free of flow distortions a high accuracy flow measurement is straightforward. We measure the flow using a NIST - traceable, 8 path ultrasonic flow meter (USM). We point out, however, that the 8 path USM, by virtue of its design, is largely immune to flow distortions and can accurately measure the flow even when subjected to significant levels of swirl and asymmetry. In contrast, to the distortion-free flow in the Reference Section, the velocity field in the Test Section is designed to replicate stack flows and has significant levels of swirl and asymmetry. Flow distortions in an industrial scale smokestack are caused by fans, reducers, and most notably a sharp corner that exhaust the flue gas into the stack. In a similar manner, flow distortions in the SMSS test section result from the sharp corner shown in Figure 29. The NIST-traceable flow measurement made in the Reference Section is used in conjunction with the mass conservation principle to determine the test section flow velocity (V_{NIST}), which in turn is used to assess the performance of CEMS flow monitors and the flow RATA.

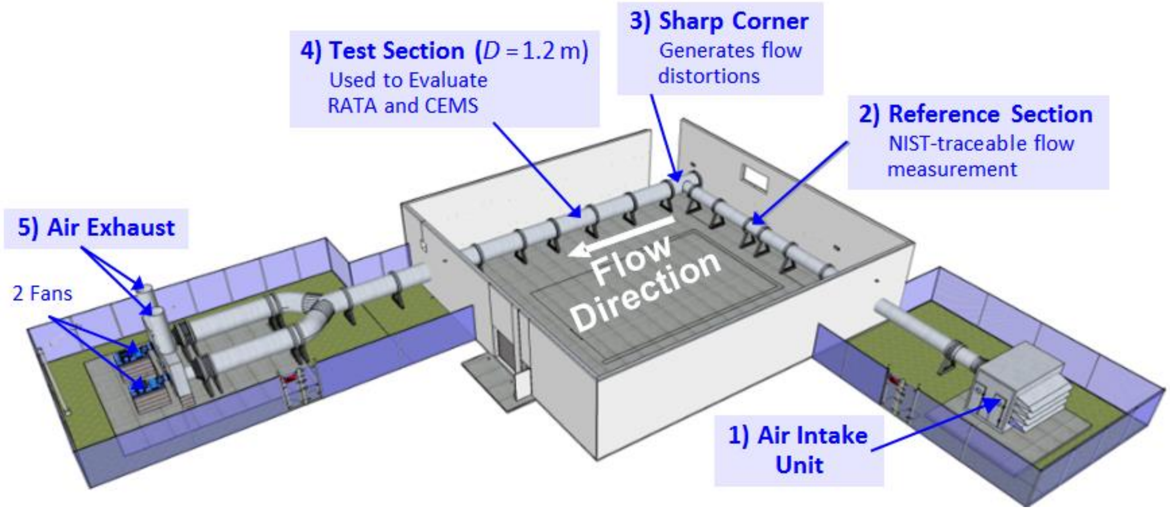


Figure 29. Schematic of the SMSS facility showing its 5-stage measurement process starting with 1) drawing air into the intake unit, 2) establishing a well-conditioned flow measured with a NIST-traceable flow meter, 3) generating distorted flow consisting of swirl and profile asymmetry, 4) assessing the accuracy of RATA and CEMS in distorted flows, and 5) exhausting flow to atmosphere.

5.2.2. CEMS Results

The majority of CEMS flow monitors used in coal-fired power plants smokestacks are single, diametric path USMs. We compared the accuracy of 3 single path USMs against an X-pattern USM. The X-pattern consists of two single, diametric paths located in the same plane, but oriented perpendicular to each. The arrows in Figure 30 B – D show the orientation of the 3 single paths in the SMSS test section and indicate the path of sound propagation between the transmitting and receiving transducers. All the paths are oriented at a 45 ° angle with the axis of the pipe, the z-axis. Path 1 lies in the yz-plane, while paths 2 and 3 lie in the xz-plane. Paths 2 and 3 comprise the X-pattern CEMS, and in this case the measured flow velocity is the arithmetic average of the flow velocity on both paths. All the USMs are installed 10 diameters downstream from the sharp corner.

In stack applications, the output of the CEMS flow monitor is adjusted to match the flow velocity determined by the RATA. For a single path USM this adjustment is usually necessary.

It corrects for large errors that can occur when a single path USM is used in distorted flows. The calibration factor corrects for flow related errors as well as for dimensional errors in the path length and path angle. In this work, we minimized dimensional errors by measuring the path lengths to better than 0.1 % and the path angles to better than 0.3 °. The resulting flow velocities (V_{path}) are determined without adjustment based on the dimensional parameters and the time of flight outputs from the ultrasonic transducer pairs on each path. Figure 3A shows the absolute errors for path 2 (◆) and for path 3 (■). The errors for these uncalibrated USMs ranged from 14 % to 17 % over the range of flow velocities, and exhibited a flow dependence of 3 %. The path 1 USM (▲) performed somewhat better, having an error between 5 % and 6 %. On the other hand, the X-pattern configuration performed remarkably well, having an error of less than 0.5 % as depicted in Figure 30A (●). The excellent performance of the X-pattern configuration suggests it may be as accurate (or perhaps even more accurate) than flow RATAs done using an S-probe. The remarkable performance of the X-pattern is attributed to its crossing paths, which partial compensation for flow errors caused by swirl. NIST is seeking industrial partners to validate these findings in field test on industrial scale smokestacks.

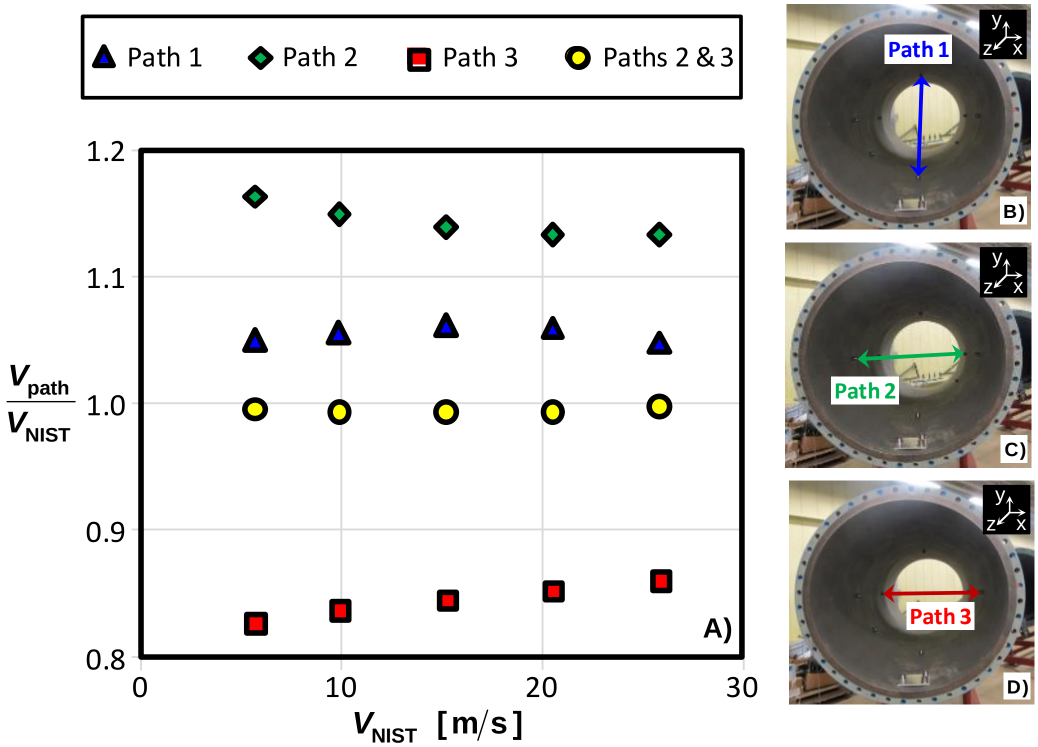


Figure 30 Data comparing the accuracy of 3 single path USMs versus an X-pattern USM. A) plot of USM path velocity (V_{path}) to NIST-traceable flow velocity (V_{NIST}), B) orientation of path 1, C) orientation of path 2, and D) orientation of path 3. (Note that paths 2 and 3 together comprise the X-pattern USM).

5.2.3. Flow RATA Results

The accuracy of the flow RATA was assessed using three different velocity probes including 1) an S-probe, 2) a prism probe, and 3) a spherical probe. The S-probe measures 2 components of velocity (i.e., a 2-D probe) while the prism probe and the spherical probe measure all 3 components of the velocity vector (i.e., 3-D probes). We individually calibrated each probe in our wind tunnel prior to starting the test. Both 3-D probes were calibrated using a yaw-nulling method over airspeeds ranging from 5 m/s to 30 m/s in 5 m/s steps and over pitch angles ranging from -45 ° to 45 ° in 3 ° steps. The spherical probe was also calibrated using a non-nulling method developed by NIST. The expanded uncertainty (i.e., uncertainty at the 95 % confidence interval) of these calibrations was roughly ±1 %. Although S-probe flow RATAs are often performed using uncalibrated S-probes, we calibrated the S - probe so that we could determine the difference calibrating the S-probe makes on the flow RATA results.

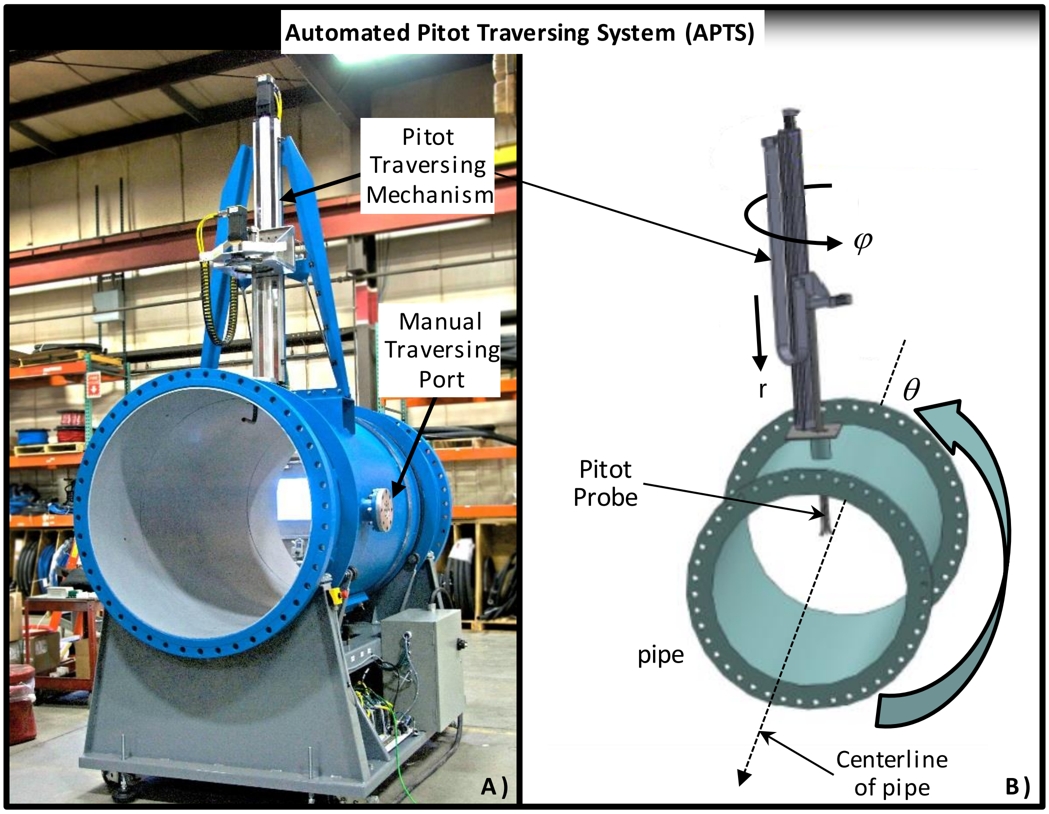


Figure 31. Photograph and schematic of NIST's Automated Pitot Traversing System (APTS) illustrating traversing directions

We compared the NIST-traceable test section flow velocity (V_{NIST}) to the velocity determined by a 12-point flow RATA (V_{probe}). The 12-point RATA consisted of 6 points spaced at the centroids of equal area located on two orthogonal, diametric chords in the same pipe cross section. The probe was moved to the traverse locations using NIST's custom designed

Automated Pitot Traversing System shown in Figure 31. We installed each probe (at different occasions) into the pitot traversing mechanism, which rotates the probe about its axis (i.e., φ-direction) to specified yaw angles, and moves the probe radially (i.e., r-direction) to each of the 6 traverse points located on chord 1. The entire pipe spool and traversing mechanism rotates 90 ° about the pipe axis (i.e., θ-direction) to align the probe with the 6 traverse points on chord 2. The flow RATA location is located 12 diameters downstream from the sharp corner shown in Figure 29.

Table 1 *Results for a 12-point flow RATA for an S-probe, a prism probe, and a spherical probe tested in SMSS facility*

Probe Type [ ]	Measurement Procedure [ ]	# of Points [ ]	V_{NIST} [m/s]	V_{probe} [m/s]	100 (V_{probe}/V_{NIST} - 1) [%]
S-probe (Uncalibrated)	Yaw-nulling	12	23.29	24.84	+6.7
S-probe (Calibrated)	Yaw-nulling	12	23.29	24.3	+4.3
Prism Probe	Yaw-nulling	12	20.62	21.37	+3.6
Spherical Probe	Yaw-nulling	12	20.61	20.88	+1.3
Spherical Probe	Non-nulling	12	20.61	20.44	-0.8

The results of the flow RATA for each probe is given in Table 1. The uncalibrated S-probe RATA overestimates the actual flow by as much as 6.7 %.[5] For a calibrated S-probe the result improved to 4.3 %, but the result still over-predicted the actual flow velocity. The prism probe gave moderately better results being only 3.6 % different. The spherical probe showed the best agreement, differing by only 1.3 % for the yaw-nulling method and by -0.8 % for the non-nulling method. The good agreement between the yaw-nulling and non-nulling method for the spherical probe provides validation of the newly developed non-nulling method. We suspect this method will have great interest to the stack testing community due to its high accuracy and significantly reduced measurement time (i.e., probe does not have to be rotated about it axis at each traverse point to find the yaw null angle).

5.2.4. Conclusion

The Scale-Model Stack Simulator (SMSS) uses air as a surrogate for flue gas and establishes smokestack-like flow conditions (i.e., turbulent swirling flow with an asymmetric velocity profile) in its 1.2. m test section. A unique aspect of the facility is that the test section flow velocity (V_{NIST}) is traceable to NIST primary standards and known to ±0.7 %. Using this facility, we found that the X-pattern CEMS flow monitor provided superior accuracy over single path CEMS, differing by less than 1 % with V_{NIST} over a flow range extending from

---

[5] The uncalibrated S-probed used the EPA default calibration factor of 0.84.

6 m/s to 26 m/s (20 ft/s to 85 ft/s). We also found S-probe flow RATA overestimated the actual flow by nearly 7 %. In contrast, 3-D spherical probe flow RATA was in excellent agreement with V_{NIST}. For the traditional yaw-nulling method the agreement was 1.3 % while for the newly developed non-nulling method the agreement was -0.8 %. The excellent results of the X-pattern CEMS and the new non-nulling method are promising and could potentially enhance the accuracy of stack flow measurements. Research efforts continue in both areas. We are testing the accuracy of the X-pattern USM over a wider range of flow conditions and we are developing a more robust non-nulling method that works over a wider range of pitch and yaw angles using fewer differential pressure transducers. We also are working with the stack testing industry to perform full-scale test to validate NIST's findings.

5.3. Recent Results from the NIST Wind Tunnel Facility

Presenters: Iosif Shinder and Aaron Johnson – NIST

5.3.1. Introduction

To expand airspeed capacity of NIST Wind Tunnel and to meet industry request to improve flow measurement in smokestacks and ducts, a 3-D Calibration Rig, Figure 32, was designed and installed. The Calibration Rig is operational in the range of velocities 5 m/s to 30 m/s, with pitch ±45° and yaw ±180°. The range of turbulence intensity which can be generated in wind tunnel is 0.1 % to 25 %. Expanded uncertainty of velocity measurement is ±0.5 %, and for pitch and yaw uncertainty is ±0.3°.

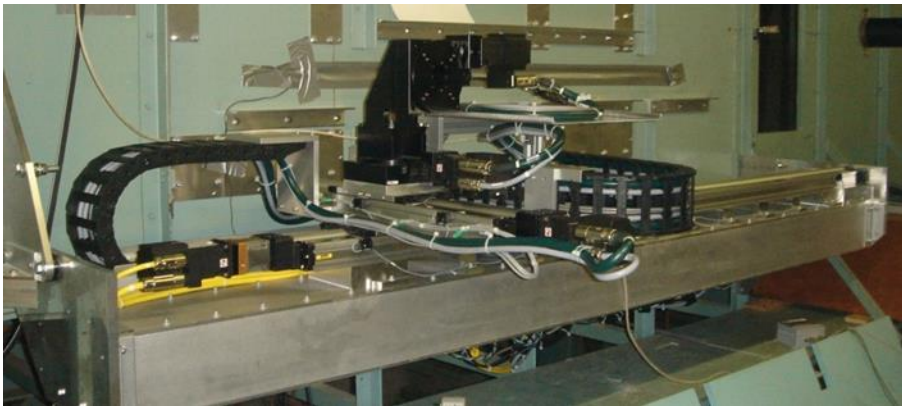


Figure 32 Photo of NIST 3-D calibration rig.

Ten 2-D (s-type) probes made by different manufacturers were tested. It was found that pitch angle, which cannot be measured by an s-probe, affects its calibration performance by as much as 5 % to 10 %.

Next, 3-D conventional multi-hole probes were calibrated according to EPA Method 2F: two prism shape probes and a spherical probe. An example of the calibration is shown in Figure 33. The spherical probe has a much smaller velocity (Reynolds number) dependence that of the prism shaped probe. We also developed a non-nulling method for the spherical probe. Both nulling and non-nulling methods were carried out at different turbulence intensities, from 0.1 % to 10 %.

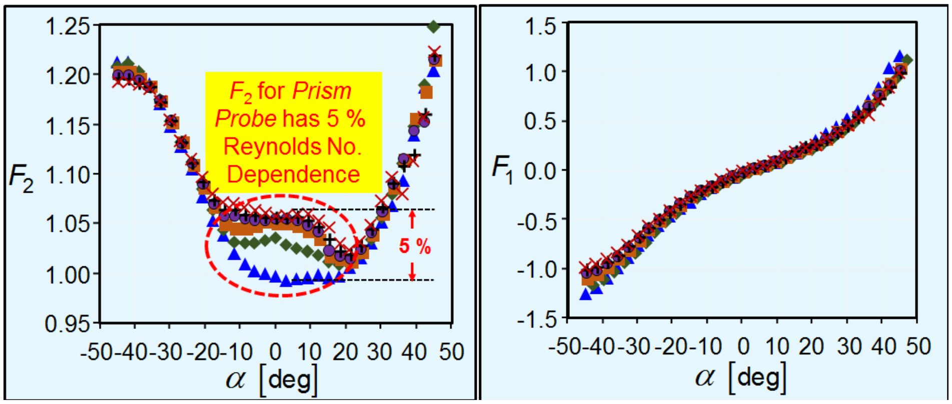


Figure 33 Pitch angle function F_1 and velocity function F_2 as a function of pitch angle.

We developed several non-conventional probes of different shapes and sizes including a spherical probe with an angle of 20° between the central hole and the remaining holes, a cylindrical shape probe, a disk shape probe, and a conic probe. Probe shapes were developed to minimize the effect of Reynolds number and pitch and yaw on probe performance.

5.3.2. Results

Calibrated S-type probes can be used to measure flow with uncertainty on the order of ±7.5 % or larger depending on complexity of the flow field. Using 3-D probes (*e.g.*, prism probe or spherical probe) and following the nulling protocol in Method 2F can reduce uncertainty to ±2 % to ±3 % provided one accounts for Reynold's number dependencies of the F_2 calibration curve, and obtains sufficiently accurate differential pressure measurements at low flows. A non-nulling method developed at NIST can be used with these 3-D probes to obtain accuracy levels of 2 % to 3 %. Both nulling and non-nulling methods are affected by turbulence and can be corrected by including quadratic dependence of the value of turbulence intensity. With this correction uncertainty of calibration can be reduced to ±1 % to ±2 %.

5.3.3. Conclusions

- The NIST Wind Tunnel calibrates pitot probes as a function of: 1) air speed, 2) pitch angle, 3) yaw angle, and 4) turbulence intensity.
- Assuming the S-probe calibration factor is 0.84 the error is on the order of 5 % for moderate pitch angles such as ±10°.
- Non-nulling probes have ±1 % to ±2 % accuracy and reduce RATA testing time by a factor of 5.

5.4. Measuring Flow with a Long-Wavelength Acoustic Flow Meter

Presenter: Keith Gillis – NIST

5.4.1. Introduction

Ultrasonic flowmeters are currently the most widely used technology to continuously monitor the flow of gaseous emissions from coal-burning power plant smokestacks. However, the uncertainty of this method using a single path typically ranges from ±5 % to ±20 %, which is unsuitable if a carbon pricing program is implemented. The Fluid Metrology Group at the National Institute of Standards and Technology (NIST) is investigating methods to reduce the uncertainty of flow measurements from smokestacks with a target uncertainty of ±1 % (k = 1). A long-wavelength acoustic flowmeter (LWAF) uses low-frequency plane waves (wavelength $\lambda > 1.7 \times D$) to measure the average axial flow speed, V, of turbulent fluid flow in a duct with diameter, D. The propagation of plane waves is predicted to be unaffected by turbulence to first order. Figure 34 shows the principle of how the flow speed is determined using the Doppler effect in a moving medium with stationary sources and detectors. Because the source is stationary, the frequency of sound propagating with or against the flow is the same, but the wavelength depends on the convective sound speed $c \pm V$, where c is the thermodynamic speed of sound, i.e. without flow. Pairs of microphones are used to determine the wavelength of sound propagating upstream and downstream of the sound source. The difference between the upstream and downstream wavelengths determines the flow speed $V = \frac{1}{2}(\lambda_{right} - \lambda_{left}) f$, and the average wavelength determines the thermodynamic sound speed $c = \frac{1}{2}(\lambda_{right} + \lambda_{left}) f$.

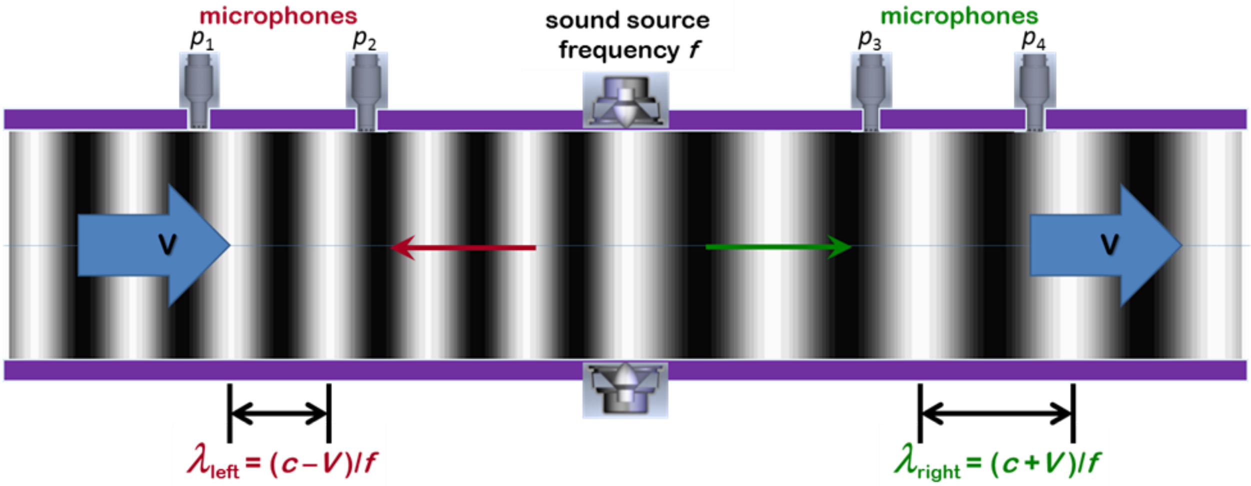


Figure 34 Sound propagation in a pipe with flow; the Doppler effect in a moving medium with stationary sources and detectors. Gas flows to the right with speed V. Sound generated at frequency f propagates upstream (λ_{left}, red arrow) with a shorter wavelength than the propagation downstream (λ_{right}, green arrow). The flow speed is determined by the difference in wavelengths: $V = \frac{1}{2}(\lambda_{right} - \lambda_{left})f$.

Our laboratory prototype LWAF consists of a series of microphones and a sound source in a 10 cm diameter circular pipe (see Figure 35). The LWAF is part of a flow system that includes a variable speed fan, a reference section including a flow straightener and a laminar flow meter (LFM) transfer standard, and an interchangeable, multiple-axis turnaround section in which swirl, asymmetric flow, and turbulence may be introduced. The variable speed fan generates flow up to 25 m/s in a 10 cm diameter pipe. The LWAF uses active sound generation (e.g. chirped sine wave or white noise) or passive measurements using flow-generated or fan-generated acoustic noise. Only plane waves propagate in the 10 cm diameter pipe for $f < 2$ kHz.

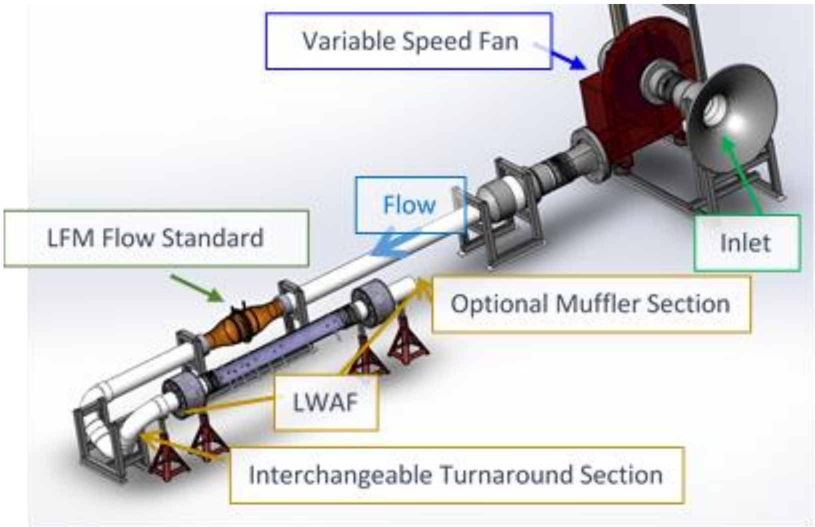


Figure 35 NIST's Prototype LWAF facility. LWAF section consists of 7 microphones and a sound source in a 1.3 m long, 10 cm diameter circular pipe. The measured flow is validated by a laminar flow meter transfer standard.

5.4.2. Results

We documented the performance of the LWAF using active sound generation with various flow profiles and speeds up to 25 m/s to determine the ($k = 1$) measurement uncertainty. In symmetric flows, the LWAF measures flow with an uncertainty $u(V) \approx 0.4$ % and measures the thermodynamic speed of sound with an uncertainty $u(c) \approx 0.01$ %. As shown in Figure 36, the flow measurement uncertainty in distorted flows with swirl, vortices, and recirculation is $u(V) \approx 1$ %. Further tests show no degradation in performance when the flowing air is very humid or when the pipe diameter is doubled. These results support the theoretical prediction that plane wave propagation is not affected by complex flow profiles to first order in the Mach number V/c.

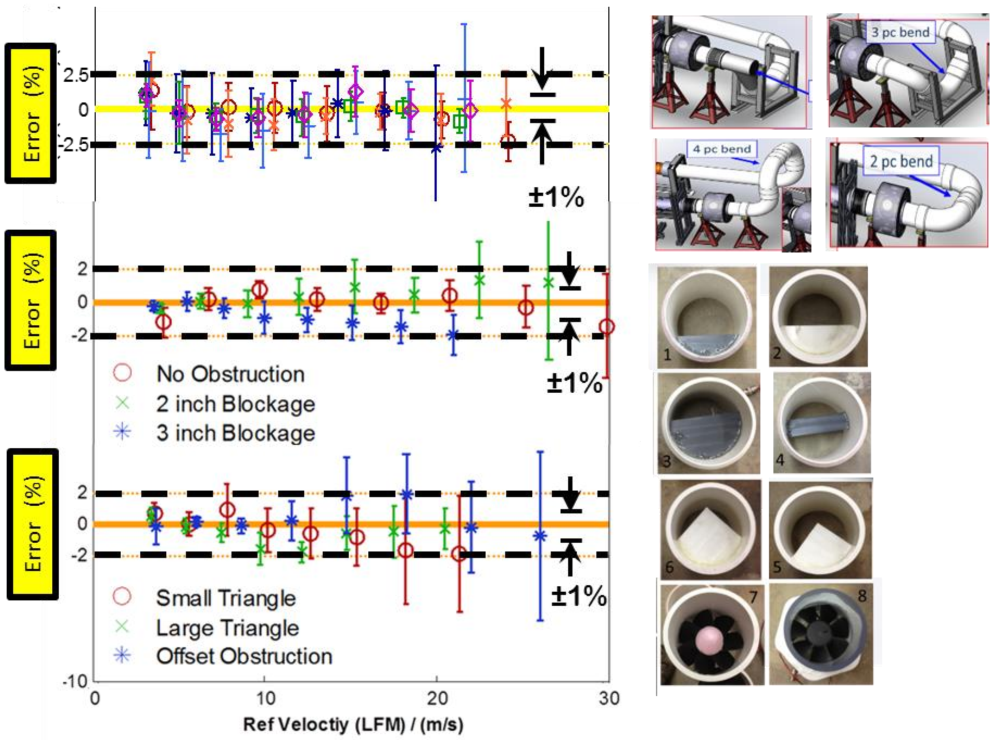


Figure 36 Error in the flow measurements compared to the LFM for various distorted flows. Top: swirl generated by a tee or multiple bends. Middle and bottom: obstructions that generate recirculation or counter-rotating flow.

To apply this technology to smokestacks, the dimensions of our prototype LWAF must be scaled up by a factor of 100. Therefore, the volume scales up by 106, and the sound pressure must scale up by the same factor to maintain the same signal-to-noise ratio. Thus, we expect active sound generation to be impractical in a smokestack. As an alternative, we are investigating whether the acoustic noise that already exists in the pipe or smokestack can be used to measure flow. Acoustic noise is generated by the turbulent flow (Reynold's number ≈ 107) and by the fans that force the combustion gases out of the smokestack. The acoustic noise fluctuations propagate in the flow as do normal sound waves, so the flow speed may be determined using a modified LWAF technique provided that the noise remains correlated over a sufficiently long distance.

We are investigating cross-correlations of flow noise in the prototype 1/100th scale LWAF. The spectral density of the measured flow noise is consistent with fluctuations smaller than the duct diameter D for $f >> V/D$. The amplitude and width of the correlation peak for broadband flow noise is shown to be dependent on V, and a model of this dependence is forthcoming. Our current work includes filtering the broadband data to determine phase shifts, modeling the effects of the radiation impedance, and examining effects on the broadband flow noise spectra. Preliminary measurements in NIST's 1/10th scale model smokestack simulator (SMSS) show similar results for frequencies up to 200 Hz, above which sound propagation is not restricted to plane waves.

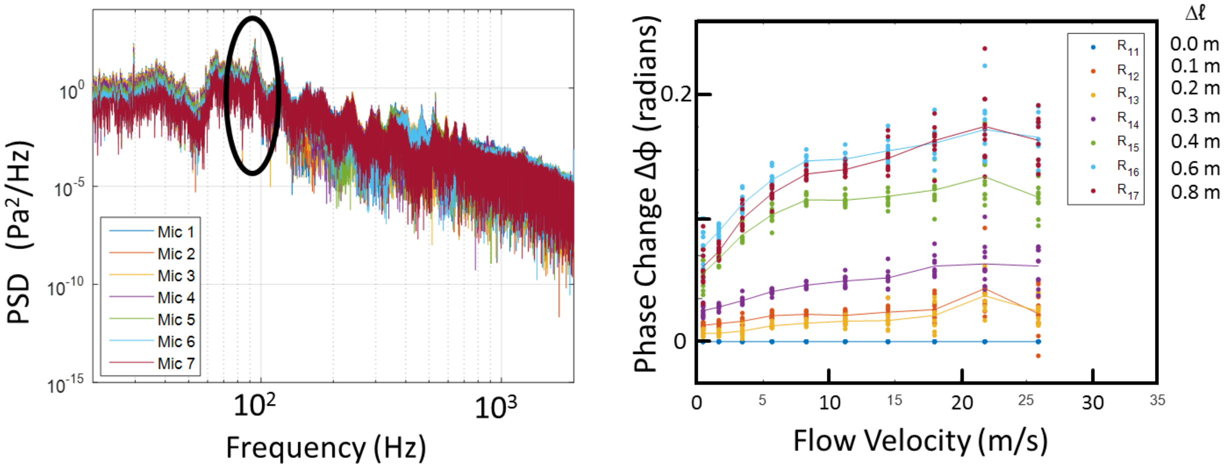


Figure 37 Left: power spectral density of noise in the 10 cm diameter LWAF. Above 100 Hz, the frequency dependence is consistent with flow-generated fluctuations. The signal at 94 Hz (circled in black) was used to calculate cross-correlations between pairs of of microphones. Right: phase difference between microphone pairs as determined from the cross-correlation as a function of flow speed.

5.4.3. Summary

Using a 1/100th scale model stack, we have shown that a LWAF with active sound generation can measure the average velocity of a turbulent, swirling, wet, air flow with a standard uncertainty of less than ±1 %. These results support the theoretical prediction that the propagation of plane waves in a pipe is not affected by asymmetric, distorted flow to first order in the Mach number. Active sound generation is impractical for power plant smokestacks because the required sound level is very high (>160 dB). As an alternative, we are investigating whether correlations in existing noise, such as flow generated noise or fan noise, can be used to determine the flow speed. Preliminary measurements in the 1/100th scale LWAF and in the 1/10th scale SMSS show that the phase difference determined from cross-correlations between microphone pairs is dependent on the flow speed in qualitative agreement with an acoustic model.

5.5. Summary of Group Discussions

Facilitators: Aaron Johnson, Rodney Bryant, John Wright, Tamae Wong – NIST

The presenters in Session 3 on NIST Research Facilities described the four facilities developed at NIST intended to establish the flow traceability of stack emission measurements. The four facilities include 1) the Wind Tunnel, 2) the Scale-Model Smokestack Simulator (SMSS), 3) the National Fire Research Laboratory (NFRL), and 4) the Long Wavelength Acoustic Flow Meter (LWAFM). Wind Tunnel research is focused on developing non-nulling 3-D probes at accuracy levels at the 1 % uncertainty level. The NIST SMSS facility establishes smokestack-like velocity fields in its 1.2 m test section and is used to assess the accuracy of the flow RATA and CEMS flow monitors. The facility was used to verify ±1 % accuracy levels of flow RATAs that used the non-nulling method developed in the NIST Wind Tunnel. In addition, the presenter showed that for two different flow fields, the absolute accuracy for an X-pattern CEMS design (not calibrated by a flow RATA) was 2 %. The LWAFM is a novel flow meter that determines flow by measuring the propagation of plane waves in a stack. The presenter demonstrated accuracy levels better than 2 % for a variety of flow installations that generated swirl and velocity asymmetries. The LWAFM is now being scaled-up to assess how its accuracy in at 1.2 m (4 ft). The NFRL facility is a near industrial-scale facility designed to evaluate the overall performance (i.e., flow and concentration) of CEMS and RATA methods aimed at measuring the stack CO_2 exhaust. The presenter explained that the facility measures the CO_2 efflux of natural gas combustion at accuracy levels of 2 % using a mass balance. Stoichiometry is used to relate measurements of natural gas flow and composition entering the facility’s burners to the post combustion CO_2 flux.

This section provides a summary, as interpreted by the editors, of responses from the group during the follow-up discussions to the previous presentations.

Specify those NIST results you feel are most promising to transfer into actual stack measurement applications.

Overwhelmingly participants indicated that the non-nulling method for 3-D probes has the most promise for field applications. The remainder of participant responses (other than non-nulling) were almost equally split between pitot probe research using the wind tunnel and research using the SMSS facility. The type of research specified by participants varied for both facilities. Suggested wind tunnel research included:

- better calibration of S-type pitot including turbulence dependence
- using the NIST wind tunnel as the "reference" for a round robin with industry pitot probe laboratories
- using the NIST wind tunnel to periodically calibrate other wind tunnels, and
- improving pitot probe designs.

Suggested research for the SMSS facility included:

- studying the accuracy of multi-path ultrasonic flow meters
- adding more variables (temperature control, moisture, gasses, etc.) to the SSMS facility for quantifying the accuracy of vender products
- studying how swirl, turbulence, and flow profile influences CEMS meters to enable software compensation in CEMS flow monitors
- quantifying the accuracy of RATA tests using different probe designs.

How would it benefit the industry if robust, yet more accurate non-nulling methods were available?

Workshop participants responded almost unanimously that accurate non-nulling would a) decrease RATA time cost, b) increase RATA accuracy, and c) reduce cost. The cost savings would be attributed to shorter RATAs. There is a significant cost to power plants when they adjust the stack flow rate from their normal load (based on customer demand) to set points required by the RATA. Shortening this duration via non-nulling methods will significantly reduce cost.

NIST results show that multipath ultrasonic flow measurements are already more accurate than the S-probe flow RATA. How can the industry make use of this information?

Some of attendees believed that the X-pattern CEMS flow monitor will always need to be calibrated against the RATA. It was stated that the X-pattern is precise, but requires calibration because the path length and path angle, which are both necessary to determine the flow velocity, are difficult to measure and are typically not accurately measured in field applications. Participants commented that the precision of the X-pattern could be realized by calibrating the CEMS flow monitor against one of the more accurate 3-D velocity probes instead of the S-probe. Still others pointed out that the price of credits is not currently driving accuracy and that using a calibrated single path has proven sufficient for some power plants. Finally, some participants thought that NIST should collaborate with EPRI and the EPA to investigate whether an X-pattern could potentially be an alternative to the RATA.

What is the next round of testing you would like to see NIST do?

Most of the workshop participants agreed that NIST should validate its findings with field testing at large/scrubbed utility stacks. Full-scale testing with 3D probes, the non-nulling technique, X-pattern acoustic flow monitors, and the fuel consumption method would expose the methods to a vast array of real world issues, testing their accuracy while improving their implementation. Participants also stated that NIST should work with the EPA to add the non-nulling method into the federal code of regulations, continue research on 3-D probes, use the SMSS facility to correlate flow disturbance levels (e.g., swirl levels, profile asymmetries, turbulence intensity) to CEMS flow meter response, and share best practices from NFRL's capability to validate carbon emissions estimates with their mass balance approach.

Should NIST findings be validated via field testing? How would this benefit the industry? What is the downside if field testing is not done?

All the participants stated that NIST findings should be validated in the field. The possible benefits of field testing included the following

- corroborating the assumed scalability of NIST research
- providing NIST with additional variables to apply to models
- accounting for the human factor in field testing
- higher quality data with better accuracy
- opportunity to address issues that arise in the field before new methods become an industry standard

The downside of not field testing included

- NIST laboratory data may not directly apply to field conditions
- aspects of NIST research may need to be made more practical for field applications (if this step is omitted there is the risk that NIST results will not be used)
- EPA might not have sufficient data to make procedures for new regulations
- no insight into complications from field conditions
- risk of error

What are the best methods for NIST to transfer its research results to the industry? Workshops? Conferences? Publications? (if so where)?

Workshop participants noted five primary methods for NIST to transfer its research results to the industry. The first and best method is to give presentations at the two main conferences of the industry: the Stationary Source Sampling and Analysis for Air Pollutants Conference organized by the Source Evaluation Society (SES), and the CEMS User Group Conference and Exhibit organized by EPRI. The second method is to continue hosting NIST workshops. The third method is to document research outputs in journals. Two suggested journals were the Journal of Air and Waste Management and Power Magazine. The fourth suggested method was for NIST to work collaboratively with the EPA and ASTM to develop consensus standards. Finally, participants suggested using online resources as well as You Tube and videos.

6. Summary of Workshop Results

Facilitators: Rodney Bryant, Aaron Johnson, John Wright, Tamae Wong – NIST

NIST hosted its second workshop on smokestack emissions with flow measurement accuracy being the focus of discussion. Industry representation included experts from the electric power generation industry, manufacturers of smokestack flow meters, Air Emissions Testing Bodies (companies that perform in situ calibrations of smokestack flow meters), environmental regulatory agencies, and national metrology institutes. The objective of the workshop was to provide a forum to exchange experiences, best practices, and ideas related to current and emerging issues with accurately measuring flow in smokestacks, a key requirement for accurately measuring smokestack emissions.

In addition to hearing from the stack measurement industry about the state of the art, technical advances, and challenges they face, NIST researchers presented their recent research results on stack flow measurement. NIST explained collaborative research efforts with the Electric Power Research Institute and the national metrology institutes of Korea and China. In NIST's National Fire Research Laboratory, (1) tracer gas dilution flow measurements (SF_6) in the NFRL exhaust ducts confirmed uniform distribution of the tracer downstream and flow measurement repeatability of ±3 % and (2) CO_2 output calculated from natural gas input flow and CEMS agreed within 2 %. In NIST's Smokestack Simulator, researchers found that the accuracy of ultrasonic-flow-meter based CEMS used in distorted, swirling conditions can be greatly improved by using two, crossing ultrasonic paths. Errors of 17 % in a single path configuration were reduced to 1 % by averaging the results of two crossed paths. In the NIST Wind Tunnel, calibrations of pitot tubes as a function of (1) air speed, (2) pitch angle, (3) yaw angle, and (4) turbulence intensity are performed. Using the NIST Wind Tunnel, researchers found that assuming the S-probe calibration factor is 0.84 leads to errors on the order of 5 % for moderate pitch angles such as ±10 °. They also learned that non-nulling probes have 2 % accuracy and reduce RATA testing time by a factor of 5. Using a 1/100th scale model stack, NIST scientists have shown that a Long Wavelength Acoustic Flow Meter can measure the average velocity of a turbulent, swirling, wet air flow with an uncertainty of less than ±1 %.

Discussion sessions facilitated with questions allowed the workshop participants to provide some feedback and a sample of the industry's technical challenges, progress, and recommendations for improving the accuracy of emissions measurements. Key outputs of the discussions following the session on AETBs were support for a full accreditation process to move the industry toward more normalized results of flow measurement. Round robin calibrations of flow sensors like the S-type pitot probes and certifying a stack for full-scale proficiency testing of AETBs for flow RATAs were identified as potential elements of an accreditation program. Participants felt that accreditation creates greater accountability for individual AETBs, motivates the standardization of best practices and personnel training, and offers better metrics for technical evaluation and oversight. In addition, the participants identified the initial cost and time investments as hurdles that prevent greater utilization of accreditation.

Following the session on Flow Measurement the discussions focused on the significant challenges to obtaining low-uncertainty measurements and the state of the art in flow measurement for power plant smokestacks. Lack of accurate stack dimensions, the impact of distorted velocity profiles, and swirling flow were common measurement challenges. Velocity profiles are dependent on stack geometry and configuration, especially in cases where one stack serves multiple generating units. Some participants agree that multi-path ultrasonic flow meters provide repeatable measurements but flow RATAs will be necessary until the accuracy of multi-path ultrasonics is proven to be insensitive to distorted velocity profiles and swirl.

Some key outputs from the discussions following the session on NIST Research Facilities were suggested research for the NIST Wind Speed and SMSS facilities. Recommendations included using the facilities to study better calibration of S-type pitot, using the NIST wind tunnel as the "reference" for a round robin with industry pitot probe laboratories, characterizing the accuracy of multi-path ultrasonic flow meters for the influence of swirl, turbulence, and flow profile, and using the NFRL to generate best practices for individual sources to improve their validation of CO_2 emissions with mass balance calculations. Workshop participants agreed that non-nulling methods for flow measurement would decrease RATA test time and cost while potentially increasing accuracy. In addition, participants recommended that NIST work with the industry to validate its findings with full-scale testing of X-pattern flow monitors, non-nulling 3D probes, and the CO_2 emissions mass balance on actual power plant stacks.

Based on the feedback from workshop attendees NIST is collaborating with EPRI to conduct field tests to validate our research findings. We plan to assess the accuracy of flow RATAs performed with 3-D probes using NIST’s non-nulling methodology. We will assess the accuracy by comparing the flow velocity determined using non-nulling methods to those obtained using the traditional nulling methods (i.e., Method 2F). Testing will be done both at a coal-fired power plant equipped with an X-pattern CEMS and at a power plant that operates on natural gas. In this way, we can assess the absolute accuracy of the X-pattern CEMS design. Testing at the natural gas plant allows for the fuel consumption method to be used as an independent verification of the non-nulling method. NIST will continue developing robust stack flow measurement capabilities at its facilities, and report progress at EPRI meetings, at the NIST workshop, at NIST websites, and in publications.

Acknowledgments

The success of any workshop is dependent on the hard work of multiple individuals. We express our sincere thanks to Gina Kline of the Fluid Metrology Group and Lucy Fox of the Firefighting Technology Group for their expert assistance and logistical arrangements for the workshop and tours. Sincere thanks are also extended to Matt Bundy and Laurean DeLauter for hosting a tour of the National Fire Research Laboratory; and to Iosif Shinder for hosting a tour of the NIST Wind Tunnel. Most importantly we thank all participants for their contributions and engaging discussions. We especially want to thank the presenters for providing valuable information that stimulated important discussions and served to open new opportunities to exchange insights. We are sincerely grateful for the candid exchange of knowledge, experiences, and best practices.

Workshop Organizers: Rodney Bryant, Aaron Johnson, John Wright, and Tamae Wong

References

[1] Johnson A, Bryant R, Wong T, Whetstone J, Dietz T, Giel D, Elam D, Swiggard S, Harman E, Woong K, Gillis K, Lee H, Shinder I, Zhang L, Grot R (2016) Measurement Challenges and Metrology for Monitoring CO2 Emissions from Smokestacks - Workshop Summary. (National Institute of Standards and Technology, Gaithersburg, MD), NIST SP 1201. https://doi.org/10.6028/NIST.SP.1201

[2] Dorko WD, Kelley ME, Guenther FR (2013) The NIST Traceable Reference Material Program for Gas Standards. (National Institute of Standards and Technology, Gaithersburg, MD), NIST SP 260-126 Rev 2013. https://doi.org/10.6028/NIST.SP.260-126rev2013

[3] US EPA (2011) U.S. EPA Ambient Air Monitoring Protocol Gas Verification Program Annual Report CY 2010. (U.S. Environmental Protection Agency, Washington, DC), EPA-454/R-11-005.

[4] Hatfield J, Pierce G, Beusse R (2009) EPA Needs and Oversight Program for Protocol Gases. (U.S. EPA, Washington, DC), Report No. 09-P-0235.

[5] Gameson L, Carney J, Hodges JT, Guenther FR (2015) NIST Report of Analysis: Environmental Protection Agency Blind Audit 2013. (U.S. Environmental Protection Agency, Washington, DC), 646.03-14-071b.

[6] Gameson L , Guenther FR (2011) NIST Report of Analysis: Environmental Protection Agency Blind Audit 2010. (U.S. Environmental Protection Agency, Washington, DC), 693.03-11-026a.

[7] Borthwick R, Whetstone J, Yang J, Possolo A (2011) Examination of United States Carbon Dioxide Emission Databases. *EPRI CEM User Group Conference and Exhibit*, (Electric Power Research Institute, Palo Alto, Ca).

[8] *Federal Register, Vol 76, No. 59: 40 CFR Parts 72 and 75; Protocol Gas Verification Program and Minimum Competency Requirements for Air Emission Testing; Final Rule* (US Government Printing Office, Washington, DC).

[9] US EPA (2017) *Acid Rain Program* (U.S. Environmental Protection Agency). Available at https://www.epa.gov/airmarkets/acid-rain-program.

[10] US EPA (2017) *Basic Information of Air Emissions Factors and Quantification* (U.S. Environmental Protection Agency). Available at https://www.epa.gov/air-emissions-factors-and-quantification/basic-information-air-emissions-factors-and-quantification.

[11] Pachauri RK , Reisinger A (2007) Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report on Intergovernmental Panel on Climate Change. (Geneva, Switzerland).

[12] Liu Z, Guan DB, Wei W, Davis SJ, Ciais P, Bai J, Peng SS, Zhang Q, Hubacek K, Marland G, Andres RJ, Crawford-Brown D, Lin JT, Zhao HY, Hong CP, Boden TA, Feng KS, Peters GP, Xi FM, Liu JG, Li Y, Zhao Y, Zeng N, He KB (2015) Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* 524(7565):335-+. https://doi.org/10.1038/nature14677

[13] Tresch T, Gruber P, Staubli T (2006) Comparison of integration methods for multipath acoustic discharge measurements. *Proc IGHEM*, pp 1-16.

[14] Bryant R, Sanni O, Moore E, Bundy M, Johnson A (2014) An uncertainty analysis of mean flow velocity measurements used to quantify emissions from stationary sources. *Journal of the Air & Waste Management Association* 64(6):679-689. https://doi.org/10.1080/10962247.2014.881437

[15] Bryant RA (2018) Uncertainty estimates of tracer gas dilution flow measurements in large-scale exhaust ducts. *Flow Meas Instrum* 61:1-8. https://doi.org/10.1016/j.flowmeasinst.2018.03.004

[16] Bryant R, Bundy M, Zong RW (2015) Evaluating measurements of carbon dioxide emissions using a precision sourceA natural gas burner. *Journal of the Air & Waste Management Association* 65(7):863-870. https://doi.org/10.1080/10962247.2015.1031294