Metrology for Monitoring Emissions from Coal-Burning Power Plants

NIST Greenhouse Gas & Climate Science Measurements Workshop

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Michael R. Moldover
Fluid Metrology Group, NIST
What is the Problem? Why is it Important?

U.S. CO₂ Emissions, By Source (EPA, 2012)
World-Wide, Coal is Most Important, IEA (2013)

Figure 10. CO₂ emissions from electricity and heat generation*

GtCO₂

- Gas
- Gas
- Oil
- Coal

1990 vs 2011
Power Plants Fueled With Natural Gas

- Volume of natural gas flowing into a power plant can be metered to better than 1 % with traceability to NIST (and SI)

- Energy content of natural gas is determined within ~1 % from composition analysis via gas chromatography. Can be checked by calorimetry.

- If required, on-line composition metering could be adopted (Rhurgas) with a reasonable cost

- Only minor measurement problems, if combustion is complete
Coal-Fired Plants: Two methods to determine CO$_2$

Fuel:
Amount & quality of coal (EIA data)

Emissions:
Flow and CO$_2$ concentration (EPA data)
Coal-Fired Plants: Two methods to determine CO$_2$
Do they agree?
Coal-Fired Plants: Two methods to determine CO$_2$
Do they agree?  **No!**

Mean $\sim$ 1.5%
FWHM $\sim$ 20%
Measurement Need

• Carbon controls (carbon tax, cap and trade) require accurate, SI-traceable, measurements of the CO₂ flux emitted by coal-burning power plants.

• Coal is too heterogeneous to serve as a surrogate for CO₂

• Current CO₂ flux measurements may be biased too high.

• NIST Objective: SI-traceable, CO₂-flux measurements with 1% uncertainty at a reasonable cost, to provide the technical basis for carbon control in US and internationally
Why are Emissions Measurements Difficult?

• Stacks are big: cannot calibrate a 10 m diameter meter in any lab

• Flow is fast: 5 m/s to 25 m/s

• High Reynolds number ~ 10^7; cannot be simulated.

• Nasty conditions:
  – Access via outside cat-walk on older stacks
  – Noisy
  – Gas is either “hot” (no scrubber 90+ °C) or “ambient & raining” (scrubber)
  – Gas is asphyxiating: composition (by volume)
    - 13.7 % CO₂
    - 3.4 % O₂
    - 74.8 % N₂
    - 8.0 % H₂O

• Flow is complicated
Flow is Complicated

Real stacks have swirl
Flow is Complicated

Real stacks have skew

Typical/Classical Velocity Profile

Atypical Velocity Profile
How are Emissions Measurements Made Today?

1) Using EPA-approved protocols, flue gas flux is continuously monitored. Composition is continuously analyzed for $O_2$, Hg, S, $NO_x$ to comply with emission controls for Hg, S, $NO_x$.

2) The instruments used for 1) comprise the CEMS = Continuous Emissions Monitoring System.

3) Typical CEMS uses two ultrasonic meters to monitor flow.

4) Annual “Relative Accuracy Test Audit” (RATA) “calibrates” ultrasonic CEMS flow monitors. Typically, the flow is surveyed with a S-probe, that is temporarily installed on the stack.

5) As the name suggests, the EPA protocols provide only relative accuracy, not uncertainty relative to primary standards.
What is NIST Doing?

1) Tie EPA-CEMS instruments and protocols to primary standards  
   (Essential for International Recognition)
   A. Calibrate Pitot probes under realistic conditions
   B. Measure sensitivity of ultrasonic flow meters to complex flows
   C. Understand/model results to generalize and scale up

2) Invent alternative flow standards for flue gas stacks  
   (to check entire measurement chain)
   A. Long Wavelength Acoustic Flow Meter
   B. Tracer Dilution
S-probe: workhorse for stack flow measurements

1. Measure Pressure Difference $\Delta p$
2. Rotate

NEEDS CALIBRATION

Flow
S-probe: workhorse for stack flow measurements

Cheap
Stable
Rugged
Passive

Can be calibrated
NIST’s wind tunnel generates well-defined airspeeds to calibrate anemometers
NIST Wind Tunnel: BTW Parameters

• Large test volume ⇒ small wall effects

• $k = 2$ uncertainty of 0.42%, 5 m/s to 25 m/s

• Low (0.1%) turbulence intensity

• Uniform flow along tunnel axis (1-dimensional flow)
Automated stage for changing pitch angle and yaw angle
Modify wind tunnel: add Grid to Generate Turbulence
Measure Effects of Grid
Measure Effects of Grid

\[
\text{turbulence intensity} \equiv \frac{\sqrt{(\bar{u} - \langle \bar{u} \rangle)^2}}{\langle \bar{u} \rangle}
\]
S-Probe, (used in EPA protocol 2)

Calibration Factor is a Function of 4 variables
1. Air speed
2. Pitch angle
3. Yaw angle
4. Turbulence intensity

EPA protocol assumes calibration factor = 0.84
(literature shows small, linear dependence on air speed)
S-probe: cannot detect pitch
Results for “typical” S-probe at 10 m/s

0.84 = EPA value

10 %
Typical CEMS Ultrasonic Flow Meter

Typically, 2 crossing paths

Measures time of flight of ultrasonic waves “sound beam” moving with and against flow ⇒ velocity component along beam and sound speed

Does not detect swirl or velocity profile distortions. If these change between calibrations the results will be biased
“Calibrate” CEMS using Calibrated Pitot Tube

- Pitot Probe traverse along two diameters in stack cross section
- Traverse Protocol Based on EPA Documents
  - 40 CFR Part 60
  - 40 CFR Part 75 (2F, 2G, 2H)

Measurement problems:
- Pitot probes not calibrated for pitch
- Velocity measured at only 2 angles
- Integration errors
Facility to study/solve measurement problems must generate known, turbulent, swirling flows

Test Section ($D_{test} = 4\text{ ft}$)

Automated Pitot Traverse

Reference Section ($D_{ref} = 3\text{ ft}$)

Fiber Glass Cone

Horizontal orientation for cost and safety

Smokestack Simulator is $1/10^{th}$ the diameter of typical stack
Smokestack Simulator

Outside Building
- Air Exhaust
- Fans
- Air Intake

Reference Section ($D = 3$ ft)
- 8 Path USM
- Flow Direction

Test Section ($D = 4$ ft)
- Flow Direction
- Corner
- CEMS USM
8 Path ultrasonic flow meter
Installed after 19 D of straight pipe (good flow)
Calibrated against NIST flow standards
Determines bulk flow to 0.5%
Calibration of USM at CEESI in Colorado

\[ \varphi = \frac{V_{NIST}}{V_{USM}} \]

Calibration Factor
Calibration Data

- Excellent Reproducibility < 0.075 %
- Expanded Uncertainty: 0.45 % to 0.58 %
- Best-ever calibration in air in this size
Long Wavelength Acoustic Flowmeter

Microphones

Loudspeakers

Radiated Wave

Reflected Wave

Outgoing Wave

Flow

Open End

distorted wave-fronts approach a plane wave

Velocity of plane wave averages over flow distortions
Long-Wavelength Acoustic Flowmeter
LWAF
1/100\textsuperscript{th} Scale

It works with
• obstacles
• complex bends
• water spray

Can we scale up to 1/10\textsuperscript{th}?
Plans

• Document performance and uncertainty of existing flow measurements in swirling and skewed flows
  - EPA Pitot traverse method
  - CEMS flow meters (Ultrasonic Flow Meters)

• Develop alternative/improved stack flow measurement techniques
  - Multi-chord and 3-D pitot traverses, advanced integration
  - Multi path ultrasonic flow meters
  - Long Wavelength Acoustic Flow Meter
  - Differential absorption LIDAR
  - Tracer Dilution Methods

• Develop benchmark data to validate Computational Fluid Dynamic (CFD) models to facilitate scale-up
Thank You

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