Probe Calibrations and RATA Results from NIST’s Wind Tunnel and Stack Simulator

NIST Workshop
Improving Measurement for Smokestack Emissions

June 28 and 29, 2017
Gaithersburg, MD
Iosif Shinder and Aaron Johnson
Goals…
To Answer the Following Questions

1. What is the accuracy of S-probe RATA?

2. Can 3-D probes make the flow RATA more accurate?
   • By how much?
   • What parameters need to be considered in a 3-D probe calibration?
   • How accurate are non-nulling methods?
Goals…
To Answer the Following Questions

1. What is the accuracy of S-probe RATA?
   **overpredicts** by 5% - 10% Depending on Pitch

2. Can 3-D probes make the flow RATA more accurate? **Yes!**
   - By how much? Expected accuracies of 1% - 3%
   - What parameters need to be considered in a 3-D probe calibration? Pitch, Yaw, **Reynolds number & Turbulence**
   - How accurate are non-nulling methods? 1% to 3% for ± 12° Pitch and ± 33° Yaw
What is the Acceptable Accuracy of Stack Flow Measurements?

1) **Accuracy 10 %**
   - relax and skip this presentation 😊.

2) **Accuracy 5 %**
   - S-probes are not sufficient;
   - 3-D probes can provide better accuracy
   - better continue pay attention

3) **Accuracy 1-2 %**
   - challenging … but we get there if NIST and Industry cooperate
   - Two new parameters must be incorporated in probe calibration
     - Reynolds number ($Re$)
     - Turbulence Intensity ($Tu$)
• Closed loop recirculating wind tunnel

• **Test volume:** 6.6 ft long × 4.9 ft wide × 3.9 ft high
  – Large test volume ⇒ small wall effects

• **Uncertainty = 0.42% for airspeeds from 16 – 100 ft/s (5 – 30 m/s)**
  – Uniform flow along tunnel axis (1-dimensional flow)
  – Automated staging to control pitch and yaw angles of pitot probes
  – Calibrations are automated
Calibration of 3 Conventional Probes

- Diameter of each probe shaft is $D = 1$ inch
- Length of each probe shaft is 6 ft
Probe Installation in Wind Tunnel

LDA Beams
LDA Sensing Volume

Pitch = 0°

Yaw Range ± 45°

Feed Through to Automated Traverse which sets pitch and yaw

Prism Probe

P1
P2
P3
P4
P5
NIST Wind Tunnel 4 Axis Traverse System

- Installed on the side of Wind Tunnel
- Single axis rotation sets **Yaw Angle** ($\beta$)
- 2 Linear motions and a rotation adjust **pitch angle** ($\alpha$) while maintaining **probe head at same position** in Wind Tunnel
- Completely automated and synchronized with airspeed measurement software
Probe Installation Inside of Wind Tunnel

- LDA Beams
- Prism Probe
- Pitch = -45°
- Pitch = 45°
S-probe Calibration

\[ V = C_p \sqrt{\frac{\Delta P_{\text{std}}}{\rho}} \cos(\beta) \]

During Calibration \((\beta = 0)\)

- S-probe calibration coefficient depends on velocity
- S-probe calibration coefficient depends on pitch (often neglected in S-probe calibrations)

**Graph:**
- \(C_{p,\text{default}} = 0.84\)
- Curves for different pitch angles: \(\alpha = 10^\circ\), \(\alpha = 5^\circ\), \(\alpha = 0^\circ\), \(\alpha = -5^\circ\), \(\alpha = -10^\circ\)

**Data Points:***
- \(C_p\) values at different velocities \((V, \text{[ft/s]})\) for each pitch angle.
Calibration Method for Prism (or Spherical) Probe
(EPA Method 2F)

1) Set airspeed; \( V_{NIST} = 16 \) to 100 ft/s (16.5 ft/s steps)

2) Set probe pitch angles: \( \alpha = -45^\circ \) to 45° (3° steps)

3) Rotate probe until \( P_2 = P_3 \) to determine Yaw Angle \( (\beta) \)

4) Measure Pitch Calibration Factor \( (F_1) \) at \( \beta \)

\[
F_1 = \frac{P_4 - P_5}{P_1 - P_2}
\]

5) Measure Velocity Calibration Factor \( (F_2) \) at \( \beta \)

\[
F_2 = \sqrt{\frac{\Delta P_{std}}{P_1 - P_2}} = V_{LDA} \sqrt{\frac{\rho}{2(P_1 - P_2)}}
\]

\[
\Delta P_{std} = \rho \frac{V_{LDA}^2}{2}
\]
Prism Probe Calibration Results

- $V_{LDA} = 16.4$ ft/s
- $V_{LDA} = 32.8$ ft/s
- $V_{LDA} = 49.2$ ft/s
- $V_{LDA} = 65.6$ ft/s
- $V_{LDA} = 82.0$ ft/s
- $V_{LDA} = 98.4$ ft/s

Graph showing the relationship between $F_1$ and $\alpha$ [deg] with different LDA velocities.
Prism Probe Calibration Results

- $V_{LDA} = 16.4$ ft/s
- $V_{LDA} = 32.8$ ft/s
- $V_{LDA} = 49.2$ ft/s
- $V_{LDA} = 65.6$ ft/s
- $V_{LDA} = 82.0$ ft/s
- $V_{LDA} = 98.4$ ft/s

$F_2$ for Prism Probe has 5% Reynolds No. Dependence
Spherical Probe Calibration Results

- $V_{LDA} = 16.4$ ft/s
- $V_{LDA} = 32.8$ ft/s
- $V_{LDA} = 49.2$ ft/s
- $V_{LDA} = 65.6$ ft/s
- $V_{LDA} = 82.0$ ft/s
- $V_{LDA} = 98.4$ ft/s

Graph showing the dependence of Reynolds number at low pitch.
Applying 3-D Probe Calibration during RATA

<table>
<thead>
<tr>
<th>Calibration Parameters</th>
<th>EPA Method 2F</th>
<th>NIST Implementation of Method 2F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitch Calibration Factor ($F_1$)</td>
<td>$F_1 = F_1(\alpha)$</td>
<td>$F_1 = F_1(\alpha, Re, Tu)$</td>
</tr>
<tr>
<td>Velocity Calibration Factor ($F_2$)</td>
<td>$F_2 = F_2(\alpha)$</td>
<td>$F_2 = F_2(\alpha, Re, Tu)$</td>
</tr>
</tbody>
</table>

- **EPA Method 2F**: $F_1$ and $F_2$ are *only* functions of the pitch angle ($\alpha$)

- **3-D probe calibration data showed the importance of accounting for Reynolds number ($Re$) dependence**

- **NIST Implementation of Method 2F**: $F_1$ and $F_2$ account for Reynolds number ($Re$) and Turbulence ($Tu$) dependence

- **Field Measured probe velocity**

\[
V_{\text{probe}} = F_2 \sqrt{(P_1 - P_2)} \cos \alpha \cos \beta \text{ at } P_2 - P_3 = 0
\]
Why is Turbulence Important?

- Wind tunnel probe calibrations are often performed in laminar flow (i.e., turbulence intensity is nearly zero)

- Probes are used in stacks where flow is certainly turbulent
  - Flow separation location and wake characteristics can vary significantly between laminar and turbulent flow
  - Pressure measurements located in laminar-wake behind probe will vary significantly from turbulent-wake
  - Turbulent velocity fluctuations induce an additional pressure at pressure ports. (This turbulent induced pressure is not present when the flow is laminar)
How do we Generate Turbulence?

**Grid** (12.5 cm spacing)

- Turbulence intensity up to 11 % for grid and up to 25 % for flag
- Turbulence intensity \( (Tu) \) is the rms of the velocity fluctuations divided by mean velocity

\[
Tu = \frac{u_{RMS}}{U} = \frac{\sqrt{(u'^2 + v'^2 + w'^2)/3}}{U}
\]

- Magnitude controlled by downstream distance from grid or flag
Does Turbulence Really Impact Accuracy?

$$V_{probe} = F_2 \sqrt{(P_1 - P_2) \cos \alpha \cos \beta} \text{ at } P_2 - P_3 = 0$$

<table>
<thead>
<tr>
<th></th>
<th>Absolute Maximum Error</th>
<th>Root-Mean-Square Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPA Method 2F</td>
<td>$F_1 = F_1(\alpha)$</td>
<td>$F_2 = F_2(\alpha)$</td>
</tr>
<tr>
<td>NIST Method 2F</td>
<td>$F_1 = F_1(\alpha, Tu)$</td>
<td>$F_2 = F_2(\alpha, Tu)$</td>
</tr>
</tbody>
</table>

Accuracy < 2% for $-45^\circ \leq \alpha \leq 45^\circ$
### 3 Non-Nulling Correlations

<table>
<thead>
<tr>
<th>Measured Parameters</th>
<th>EPA Method 007</th>
<th>NIST Method 007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized Pseudo Dynamic Pressure</td>
<td>$\frac{P_1 - P_t}{\tilde{P}_{EPA}} = \tilde{F}(\alpha, \beta)$</td>
<td>$\frac{\tilde{P}<em>{NIST}}{\Delta P</em>{LDA}} = \tilde{F}(\alpha, \beta, Re, Tu)$</td>
</tr>
<tr>
<td>Pitch Angle Function</td>
<td>$\frac{P_4 - P_5}{\tilde{P}<em>{EPA}} = F</em>\alpha(\alpha, \beta)$</td>
<td>$\frac{P_4 - P_5}{\tilde{P}<em>{NIST}} = F</em>\alpha(\alpha, \beta, Re, Tu)$</td>
</tr>
<tr>
<td>Yaw Angle Function</td>
<td>$\frac{P_2 - P_3}{\tilde{P}<em>{EPA}} = F</em>\beta(\alpha, \beta)$</td>
<td>$\frac{P_2 - P_3}{\tilde{P}<em>{NIST}} = F</em>\beta(\alpha, \beta, Re, Tu)$</td>
</tr>
</tbody>
</table>

- Preliminary EPA Method 007 **will not work for** 3-D probes for which $\tilde{P}_{EPA} = 0$

- NIST Method 007
  - accounts for Reynolds ($Re$) number and Turbulence ($Tu$) dependence
  - works well for several probes over wide range of pitch and yaw since ($\tilde{P}_{NIST} > 0$)
Non-Nulling: Example of Velocity Dependence

Spherical Probe

![Graphs showing velocity dependence](image)

- $\alpha = 0^\circ$
- $\alpha = -21^\circ$
- $\alpha = -33^\circ$
- $\alpha = -45^\circ$

Velocity (ft/s):
- 16.4 ft/s
- 49.2 ft/s
- 82.0 ft/s
- 32.8 ft/s
- 65.6 ft/s
- 98.4 ft/s
Custom Probe Shapes Designed at NIST

- NIST is researching various probe designs

- Probe performance is based on *probe geometry* and *hole placement*

- Goal is to identify probes that are *highly immune* to Reynolds number effects and Turbulence over a wide range of pitch and yaw
A Facility Designed to Assess the Flow Measurement Accuracy of CEMS and RATA

Three Design Criteria

1) Facility must have *CEMS and RATA equipment* commensurate to what is used in industry

2) Facility must *create smokestack-like flow conditions*

3) Facility must *establish NIST traceable velocities* \( V_{NIST} \) to compare CEMS and RATA
Scale-Model Smokestack Simulator (SMSS)

1) 8 path ultrasonic flow meter measures flow to better than 0.5%
2) Stack flow conditions (high swirl and skewed velocity profile) realized by sharp corner section
3) RATA equipment installed in SMSS Test Section
   - RATA equipment – probes calibrated
   - Wind Tunnel installed in the automated traverse system
RATA Performed using an Automated Pitot Traverse Unit Installed in 4ft Test Section

- Pitot probe can be positioned to any desired location in the cross section
  - Probe moves radially to a selected RATA point
  - Probe rotates to determine Yaw angle ($\beta$)
RATA Performed using an Automated Pitot Traverse Unit Installed in 4ft Test Section

- Pitot probe can be positioned to any desired location in the cross section
  - Probe moves radially to a selected RATA point
  - Probe rotates to determine Yaw angle ($\beta$)
  - Traverse arm rotates to in $\theta$-direction to measure RATA points on different chords

- Completely Automated via LabVIEW software
RATA Measurement Location

RATA performed 12 D from the Corner

Traverse Chord

Cross section

Z

90°

0° ➔ y

270°

180° ➔ x

Prism Probe

Spherical Probe

S-probe

Flow Direction
RATA: Velocity Profile, Yaw and Pitch Angles

Automated Probe Traverse

Normalized Axial Velocity

Yaw Angle ($\beta$)

Multiple Nulls found close to the wall

Normalized Axial Velocity

- CFD
- SP 2016
- SP 2017
- Prism
- Sphere

40
30
20
10
0
-10
-20
-30
-0.6 -0.4 -0.2 0 0.2 0.4 0.6
y/D

Traverse Chord

Cross section
**RATA:** Velocity Profile, Yaw and Pitch Angles

![Image of Automated Probe Traverse]

**Normalized Axial Velocity**

- CFD
- SP 2016
- SP 2017
- Prism
- Sphere

**Pitch Angle (\(\alpha\))**

**Yaw Angle (\(\beta\))**

- Inlet Cone

**Traverse Chord**

- Cross section

**Orientation**

- 0°
- 90°
- 180°
- 270°

**Experimental Traverse Location**

**Inlet Cone**
S-Probe RATA along 2 Diametric Chords

### # of Points | \( V_{\text{NIST}}, [\text{ft/s}] \) | \( V_{\text{Probe}}, [\text{ft/s}] \) | % Difference
--- | --- | --- | ---
12 | 76.40 | 81.50 | + 6.7 %
24 | 76.40 | 81.37 | + 6.5 %
48 | 76.40 | 80.40 | + 5.2 %

- In all cases the **S-probe over predicts** the actual flow
- Slight increase in accuracy with more traverse points
- \( C_p = 0.84 \); **What is the accuracy if we use a calibrated S-probe?**
In all cases the **S-probe over predicts** the actual flow

Slight increase in accuracy with more traverse points

$C_p = 0.84$; **What is the accuracy if we use a calibrated S-probe?**

**Calibration improves accuracy**

<table>
<thead>
<tr>
<th># of Points</th>
<th>$V_{NIST}$, [ft/s]</th>
<th>$V_{Probe}$, [ft/s]</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>76.40</td>
<td>81.50</td>
<td>+ 6.7 %</td>
</tr>
<tr>
<td>24</td>
<td>76.40</td>
<td>81.37</td>
<td>+ 6.5 %</td>
</tr>
<tr>
<td>48</td>
<td>76.40</td>
<td>80.40</td>
<td>+ 5.2 %</td>
</tr>
<tr>
<td>12</td>
<td>76.40</td>
<td>79.72</td>
<td>+ 4.4 %</td>
</tr>
</tbody>
</table>

$C_p (Re, \alpha) = 0.84$
Prism Probe RATA along 2 Diametric Chords

45° Orientation

135° Orientation

• The Prism probe over predicted the actual flow
• Better accuracy than calibrated S-probe (6.7 % uncalibrated)

<table>
<thead>
<tr>
<th># of Points</th>
<th>$V_{\text{NIST}, \ [ft/s]}$</th>
<th>$V_{\text{Probe}, \ [ft/s]}$</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>67.64</td>
<td>70.10</td>
<td>+ 3.6 %</td>
</tr>
</tbody>
</table>
The Spherical probe over predicted the actual flow.

Better accuracy than S-probe (6.7%) and the Prism probe (3.4%).

<table>
<thead>
<tr>
<th># of Points</th>
<th>( V_{\text{NIST}}, \ [\text{ft/s}] )</th>
<th>( V_{\text{Probe}}, \ [\text{ft/s}] )</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>67.63</td>
<td>68.52</td>
<td>+ 1.3 %</td>
</tr>
</tbody>
</table>
Non-Nulling Method Works Well!

- NIST has developed a **robust, high accuracy non-nulling method**
  - Improvement over Method 007 (i.e., more accurate fit over wide range of pitch and yaw)
  - Accounts for turbulence ($Tu$) and Reynolds number ($Re$) dependence

- Recap Spherical Probe RATA Results
  - Measured $V_{RATA}$ and $V_{NIST}$
  - Accuracy evaluated by $% \text{Diff} = 100 \left( \frac{V_{RATA}}{V_{NIST}} - 1 \right)$

<table>
<thead>
<tr>
<th># Points</th>
<th>% Diff</th>
<th>Method</th>
<th>$Tu$ (During Cal.)</th>
<th>$Tu$ (During Use)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>+ 1.3 %</td>
<td>2F</td>
<td>0 %</td>
<td>10 %</td>
</tr>
<tr>
<td>12</td>
<td>- 0.8 %</td>
<td>Non-Null</td>
<td>10 %</td>
<td>10 %</td>
</tr>
</tbody>
</table>

- Results are preliminary pending field test
1) Wind Tunnel Probe Calibrations
   ❖ **S-probe** has a large pitch dependence (10 % effect) that cannot be accounted for via calibration.
   ❖ **3-D Probes** highly accuracy if Reynolds dependence and Turbulence characterized
   ❖ Robust non-nulling techniques have been developed and work well!
   ❖ New probe designs less sensitive to turbulence and Reynolds number are being developed

2) SMSS Facility Results
   ❖ **RATA Testing**
     o Spherical probe exhibited best accuracy ($\pm 1 \%$)
     o prism probe ($\sim +3 \%$)
     o **S-probe** ($\sim +6 \%$)
   ❖ SMSS Facility has large yaw angle $\sim 35^\circ$ near the wall
   ❖ Accuracy of Non-nulling method is the same as yaw-nulling method (within 1 %)
Questions?