CTM-041 and Potential Revisions to EPA Reference Method 2H

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Summary

Conditional Test Method 41 (CTM-041) was developed as part of the EPRI Rectangular Duct Wall Effects Study[1] to allow sources that make measurements in duct locations to adjust their flow data to account for wall effects. In addition to filling a void the flow reference methods, CTM-041 includes a number of improvements over EPA Reference Method 2H. This paper discusses the development of the CTM-041, some practical aspects regarding its application, and an effort to incorporate the improvements into Method 2H.

Introduction

The Acid Rain and NO_X Budget Programs convey a monetary value to CEMS data and necessitate precise, accurate measurements. A positive bias in the CEMS measurements translates directly into over-reporting of allowances with millions of dollars of impact. Rising allowance prices and the advent additional trading programs under the Clean Air Interstate Rule and Clean Air Mercury Rule in the near future only makes potential bias concerns more pressing and pertinent.

In the 1990s, EPRI undertook a research project to address utility concerns over apparent discrepancies in CEMS measurements. Although flow measurement was not the sole culprit, it was found to be a significant contributor and that much of the bias was related to the EPA reference method procedures themselves. In response to the EPRI study, EPA initiated a number of field tests to evaluate possible modifications to the stack flow reference method procedures.

One problem uncovered in EPRI and EPA studies was the inherent bias that is associated with the equal area traverse procedure in Reference Method 1. The traverse point selection procedure assumes that the average flow for a given area in the stack is represented by the flow measured at the centroid of that area. While this assumption is essentially true for the "bulk flow" in the central portion of the stack, it does not apply for the areas near the wall. Such an assumption invariably results in overestimation of the actual average velocity used in flow rate calculations because it does not account for viscous shear that causes the velocity to drop off significantly near the stack walls. This effect is illustrated in Figure 1, which shows the typical velocity and shear stress distributions near a stack or duct wall. [2]

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[1] Impact of Viscous Shear Wall Effects on Flow Measurements in Rectangular Ducts: Final Report, February 2003, EPRI, Palo Alto, CA, American Electric Power, Dallas, TX, Southern Company Services, Birmingham AL, Alliant Energy Corporation, Madison, WI, PacifiCorp Electric Operations, Salt Lake City, UT, and Tennessee Valley Authority, Chattanooga, TN: 2003. 1007649.

[2] The terms "duct" and "stack" are and can be used interchangeably throughout this paper.

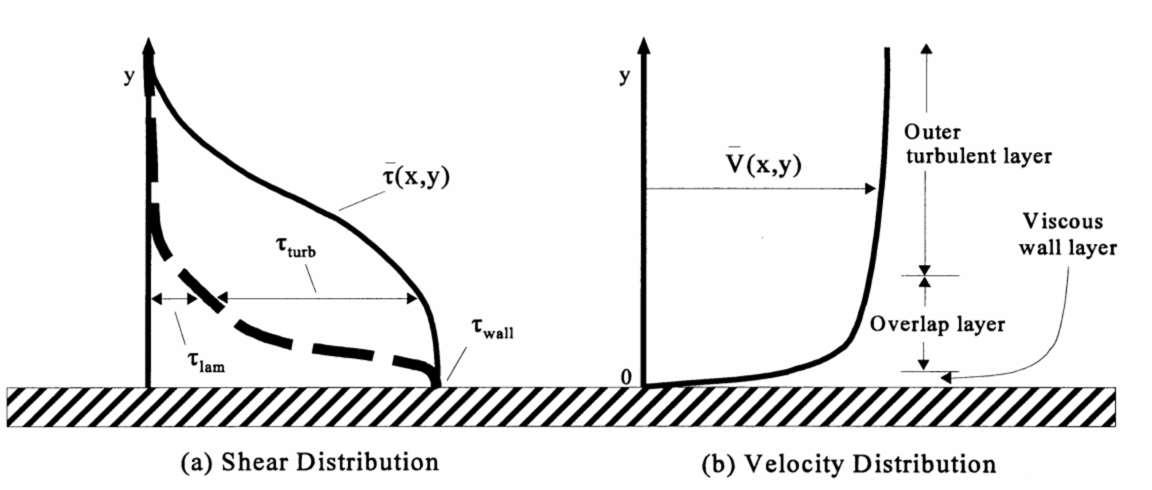

Figure 1. Typical Velocity and Shear Distributions in Turbulent Flow Near a Wall

In 1999, EPA promulgated a number of stack flow reference method revisions including Reference Method 2H, which was intended to address the problems with the equal area traverse procedure. However, Method 2H could only be used on circular stacks. No wall-effect corrections were allowed for flow measurements in rectangular ducts even though the same viscous shear wall effect occurred in those locations. In fact, the wall effect related bias is even more pronounced in rectangular ducts than on a circular stack since:

- **There is more wall surface.** The ratio of the stack wall perimeter to the total stack cross sectional area is greater on a rectangular duct than on a circular stack. In other words, the portion cross-sectional area influenced by wall effects is greater on a rectangular duct--more wall, more wall effects.

- **The test points are farther from the wall.** Since the traverse points on circular stacks are closer to the wall, a portion of the wall effects may sometimes be reflected in the velocities measured. In contrast, the traverse points for rectangular ducts generally lie wholly in the bulk flow region, which is virtually unaffected by the wall. Thus, little, if any, of the influence of wall effects will be seen.

- **Wall effects are more intense in the corners.** Wall effects on rectangular ducts would also be expected to play a larger role because of the corners. The velocity drop off in the corners is greater because the flow is impacted by viscous shear stresses of velocity gradients from two adjoining walls.

Method Development

The EPRI Rectangular Duct Wall Effects Study included two comprehensive, thoroughly peer-reviewed[3] field tests to validate a measurement-based reference method to calculate

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[3] The peer reviewers for the study included not only industry personnel and academic/consulting experts but also federal and state regulators as well.

the wall effect adjustment factors for rectangular ducts. EPA participation was actively encouraged in the study, and we received good support and cooperation from the Agency, with EPA's Emission Measurement Center (EMC) to take the lead although the study was also closely followed by Clean Air Markets Division (CAMD).[4]

While the equations are a little more complex for rectangular ducts simply due to the geometry, the method developed under the EPRI study follows the same general approach as used in Method 2H. Under both methods, replacement velocities are determined for each exterior Method 1 equal-area sectors by taking measurements at one-inch intervals from the wall and an additional point (v_{drem}) representing the centroid of the remainder of the equal-area at each test port location. The velocity for each one-inch band is approximated as the average of the two velocities measured at its boundaries with the velocity at the wall, v_0, known to be zero. Near velocity measurements are numerically integrated as a Riemann sum in a manner analogous to trapezoidal rule of calculus to calculate wall effects corrected velocities for each exterior equal area. The replacement velocities are simply the wall-adjusted flow divided by the area of the section. The wall effect corrected velocities are then used, in conjunction with unadjusted velocities from a regular Method 1 traverse, to calculate a wall effect adjustment factor (WAF).

The field tests were conducted at two representative utility monitoring locations. The first set of tests was performed at Southwestern Electric Power Company's Welsh Generating Station Unit 1, which is a 558 MW opposed-wall, coal-fired dry bottom boiler, on a vertical, rectangular stack with a cross section of 12' x 18.5'. The second set of tests was conducted at Gulf Power Company's Crist Generating Station Unit 5, a 75 MW tangentially-fired coal boiler at test location in a straight horizontal duct section with a cross section of 7.3" x 12.7" downstream induced draft (ID) fans.

At each field test site, the program consisted of a series of preliminary tests, three sets of "wall effect" tests and "corner effect" tests using two manual test teams and a set of four autoprobes.[5] The viscous shear effects were categorized along available three walls at both sites and two corners at Crist and in all four corners at Welsh. The autoprobes were also employed to conduct three overnight wall effect tests at each site. The test plans included a number of special features intended to address specific concerns:

Testing from Multiple Walls. Testing was conducted from ports on multiple walls to assess the efficacy of conducting near wall measurements from test ports located on a single duct wall.[6]

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[4] Method development was summarized in greater detail a previous paper: Norfleet, Stephen K. *Correcting Flow Measurements for Wall Effects in Rectangular Ducts and Stacks*, 2003 EPRI CEM Users Group Meeting, San Diego, California, May 2003.

[5] Autoprobes are automated, modified S-type probe flow traversing devices developed by United Sciences, Inc.

[6] Unlike circular stacks, where test ports must be located 90 degrees apart, Method 1 only requires that test ports be located along one wall of a rectangular ducts; and it is impractical, and many times impossible, to install test ports or make flow measurements from all four walls.

Multiple Load Testing. The test program included "overnight" wall effects tests at low- and mid-loads to further demonstrate that there is no need to require testing at separate loads. Fluid dynamic theory, as well as the data from EPA's flow study[7], indicates that the viscous shear wall effects are independent of the flue gas velocity. EPA's Flow Reference Method Testing and Analysis Findings Report states that "there is no obvious relationship between the percent change in velocity due to wall effects and the average velocity in the baseline traverse."[8] Nonetheless, EPA currently requires separate wall effect tests for RATAs at each load level. The overnight tests were included for EPA's consideration in dropping the multiple load testing requirement.

Corner Effect Tests. The velocity drop off is more intense in the corner of ducts where the flow is impacted by viscous shear stresses from two adjoining walls as opposed to one wall elsewhere. "Slider ports" were installed on the stack walls at both Welsh and Crist so that the impact of the more intense viscous shear effects in the corners could be evaluated. The slider port configuration allows the tester to adjust the linear position of the port along the wall so that the entire corner region can be measured.

Special tests were included in the program to assess the corner effects on the duct flow. However, the intense testing and duct modifications needed to measure this phenomenon would not be practical, or even possible, at all rectangular duct sources. Instead of conducting corner tests at all sites, the results of these corner tests were used to address the corner effect both in the default adjustment factors and wall effects measurement approach.

Replicate Reference Method Flow Testing. Because the goal was the promulgation of a new reference method, it was important to gauge the uncertainty of the method. The test programs included numerous replicate tests to help assess the variability of the method via statistical analysis.

QA/QC Procedures. The QA/QC procedures of Methods 2, 2G and 2F were followed during this test program. Since minimizing unit variability is critical when determining wall effects, efforts were made to operate the units in a steady, consistent manner during the test program and numerous process parameters were recorded as indices to assess unit variability and data quality.

Highlights of Study Results

The field tests demonstrated the viability of the wall effects measurement approach. The impact of viscous shear wall effects on the flow measurements at the Welsh and Crist test locations was determined to be 4.1% and 5.7%, respectively. Supplemental analysis showed that, while dependent on duct geometry, such results will be typical for many rectangular ducts from utility and industrial boilers. The study also showed that:

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[7] EPA Flow Reference Method Testing and Analysis: Findings Report, US EPA, Acid Rain Division, EPA/430-R-99-009a, May 1999, Figure 5-7, p. 5-14.

[8] Id., p. 5-14.

- The accuracy of the logarithmic-overlap law can be harnessed to reduce the number of measurements needed to determine a wall effects adjustment factor. The logarithmic-overlap law has been demonstrated effective for a wide range of applications including the units included in this study as well as those included in earlier EPA and EPRI studies. Through essentially a simple curve fitting exercise based on two near wall measurements at each port, the logarithmic-overlap law can be employed to categorize the first 12 inches from the wall. In addition to exhibiting a lower WAF variability, this approach also solves a problem that has plagued EPA Reference Method 2H, where an accurate WAF assessment could not be fully made if the ports protruded into the stack by one inch or more.

  In the proposed method this takes the form of an alternative "measurement reduction" option that may be used in lieu of measurements at each near wall point. Measurements would still be required at the first available one-inch interval and at the twelve-inch interval as well as any necessary d_{rem} points, but the other values would be calculated based on the following simple relationship derived from the logarithmic overlap law:

  $$V_d = V_2 - (V_2 - V_1)\frac{\ln(d/12)}{\ln(y_1/12)}$$

  where:

  V_d = velocity at distance d from wall, ft/s
  V_1 = velocity at measured at the closest available one-inch interval from wall, ft/s
  V_2 = velocity at measured at a distance of 12 inches from the wall, ft/s
  y_1 = distance of the closest available one-inch interval from the wall, in.
  d = distance d from wall, in.

- The logarithmic-overlap law can also be used, in conjunction with a few conservative assumptions, to develop duct specific default WAF values. This option yields conservative WAF values that are based on viscous shear theory and, unlike the present defaults in Method 2H, take into consideration the geometry of the duct. While these default factors would be conservative and, thus, not offer sources the full correction, the option of such a non-measurement-based approach would be welcomed and reasonable for applications where additional measurements (or, if necessary, the installation of additional test ports) would prove difficult.

  In the method, the logarithmic-overlap law was employed to yield conservative default values by making three relatively simple combined changes to the logarithmic-overlap law approach previously outlined: 1) by using a conservative roughness value of 0.0002 ft, 2) by substituting the first regular traverse point velocity for the 12? point, and 3) employing the logarithmic-overlap law beyond the logarithmic-overlap region to calculate $M1_y$ and d_{rem} velocities. In the method, the duct specific default is calculated in the following manner:

$$V_d = V_2 \left[\frac{\ln \dfrac{d}{0.0024} + 0.41(8.5)}{\ln \dfrac{y_2}{0.0024} + 0.41(8.5)} \right]$$

where:

V_d = velocity at distance d from wall, ft/s
V_2 = velocity measured at the first regular equal area traverse point, ft/s
y_2 = reference distance[9], in.
d = distance d from wall, in.

The inherent conservative nature of the duct specific default approach is illustrated in Figure 2.

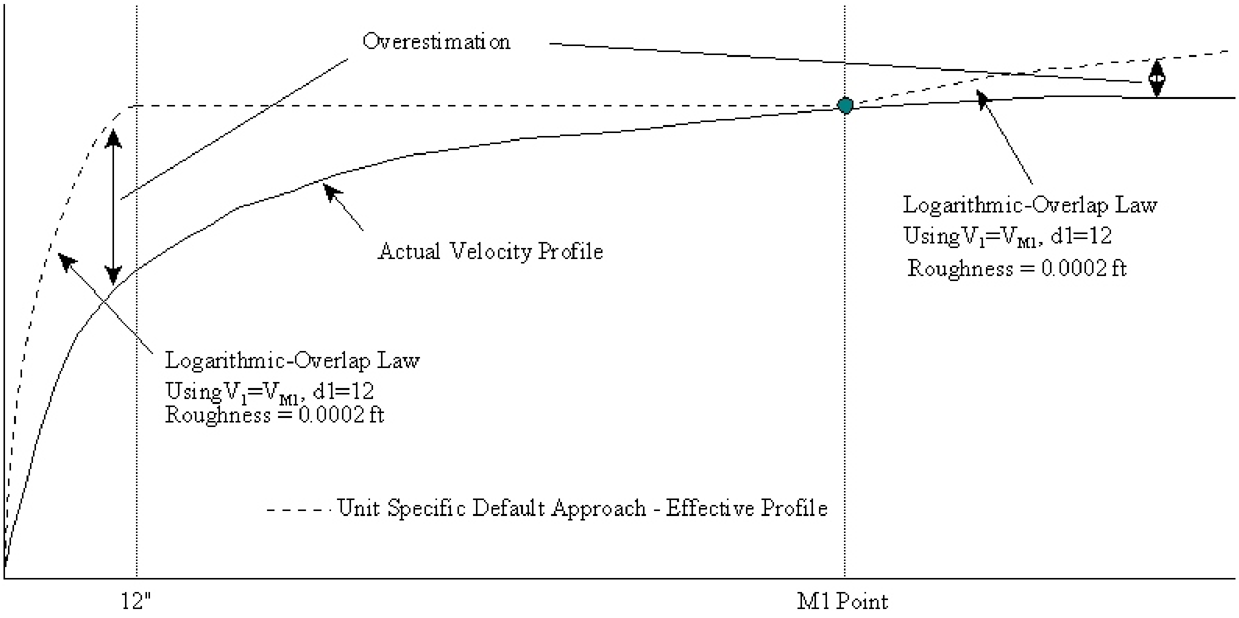

Figure 2. Duct Specific Default Approach

- There is no apparent load or Reynolds number (i.e., velocity) related effect on WAF values nor do wall effects vary depending upon the measurement method used. WAFs can be determined at a single load level and applied to subsequent RATAs

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[9] To calculate the velocity at the near wall one-inch intervals (1 inch to 12 inches) using the equation, use y_2 = distance from the wall of the first Method 1 equal area traverse point unless the distance is greater than 12 inches then use y_2 = 12 inches. To calculate the velocities at the d_{remx}, d_{remy}, and d_{M1y} locations, use y_2 = distance from the wall of the first regular equal area traverse point. If the respective distance (d_{remx}, d_{remy}, or d_{M1y}) is greater than 12 inches but less than the distance from the wall of the first Method 1 equal area traverse point, substitute the velocity measured at the first Method 1 equal area traverse point for desired velocity.

conducted at various load levels regardless of the methodology used presuming the RATA includes the same number of traverse points on which the WAF determination was based. Since the factors that influence wall effects will not change appreciably over time, one should be able to continue to use a historic WAF unless changes are made to the duct or stack.

- As expected, more intense viscous shear was seen in the corner regions of rectangular ducts. The measurements correlated well with those predicted using a Darcy friction factor-based approach. The wall effects method was revised to include the Darcy friction factor-based corner correction equation as well as a default factor of 0.995 that would represent the low range of corner impact like that seen at Crist.

- As was illustrated in previous EPRI and EPA studies, it is critical that stack flow remains relatively consistent during each wall effect run to ensure accurate results. Expediting quick wall effects runs by decoupling the test from the RATA helps. Averaging the results of three or more wall effects test runs also reduces WAF variability.

- Presently, Method 2H specifies that the WAF is applied to the each run of the associated RATA. The application of the adjustment can be made simpler and more akin to the standard displacement thickness δ^*-approach[10] by instead applying the WAF as adjustment to the cross-sectional area. The wall effects adjusted stack flow would be calculated using the following relationship:

$$Q_{adj} = v_{avg}\left(WAF \times A\right)$$

where,

Q_{adj} = wall effects adjusted volumetric stack flow, scf/s
A = duct cross-section area at reference measurement location, ft^2

This cross-sectional area correction results in the exact same flow values as the current Method 2H approach. However, it would not require a three-load RATA to implement since the correction would be applied to both the cross-sectional area used to calculate the RATA flow values and the CEMS flow values.[11] The cross-sectional area approach completely decouples the wall effects test from the RATA, so that the correction conceivably can be made at any time. Application of the WAF is also not dependent on whether the flow meter is subject to a bias adjustment factor (BAF).

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[10] In practice, the wall affects adjustment factor approach of Reference Method 2H is very similar to displacement thickness, δ^*, a concept often used in wind tunnel applications. While determined experimentally, δ^* is the theoretical distance by which the duct wall would have to be moved inward to give the same flow if viscous forces were absent. A Reference Method 2H adjustment factor is essentially equal to one minus δ^* times the ratio of the duct perimeter to cross-sectional area.

[11] Under the current 2H approach, the correction is only applied to the RATA; thus, the flow meter polynomial k-factors must be changed to assure that the adjustments are also reflected in the CEMS measurements, which triggers a three-load RATA under 40 CRF Part 75.

This very useful modification was well received by the peer reviewers, including those from EPA.

- Duct cross-bracing can influence near wall measurements. Based on this finding, the method was revised to require that measurements be made from at least four ports excluding ones where the flow in the near wall region is disturbed.[12] Measurements from at least four ports seem necessary based on the results at Crist and the wall effects test data reported for circular stacks.

Method Application

The field tests and the method itself received a great deal scrutiny by the peer reviewers, and the Agency was provided numerous opportunities to comment during the study. Given this, albeit there was some delay, the rectangular ducts wall effects method that was published in the EPRI report was posted to EPA's web site as CTM-041 with little revision. While, initially, there was some concern over measurements when ash buildup was present, this issue has since been resolved successfully. The Agency is even allowing sources to retroactively apply the WAF back to the beginning of the year when the test is performed (including allowing sources to resubmit past quarters).

Since it has been released as a conditional test method, CAMD has required petitions in order to use CTM-041, but these petitions are just a formality have been readily accepted. CAMD has also provided reporting instructions for sources using CTM-041 data. While most test data must simply be maintained on file, a summary of the results do need to be included in each quarterly report for which the WAF is applied. Initially, an ad hoc approach was implemented through the RT 910 "cover letter" records but the agency is now planning to phase in the use of a new record EDR record type (RT532) specifically for CTM-041 WAF results.

As part of the EPRI project, RMB developed spreadsheet tools to perform the calculations necessary to reduce the measurement data as well as calculate WAF values using the logarithmic-overlay law-based "measurement reduction" and "duct specific default" options, discussed later in this report, which are included in the method. A copy of the Method CTM-041 calculation spreadsheet is available form both the RMB and EPA web sites.

To assess the use of this new method, the 2004 EDR files were analyzed to extract CTM-041 information for Acrid Rain sources. The results of this analysis are shown in Table 1. As of the fourth quarter of 2004, there were 75 rectangular duct locations where CTM-041 had been used, with 36 locations applying the measurement-based approach and 39 locations using the unit specific default approach. The measurement based WAF corrections averaged about 4.0% and ranged from 2.0% to 7.1%. The unit specific default values ranged from 3.8% to 1.5%, with and average of 2.8%.

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[12] Historically, cross-bracings have not been considered to be flow disturbances under EPA Reference Method 1. This seems reasonable since the cross-bracings appear to have less impact on measurements outside the near wall region.

	Measurement Approach (36 Locations)		Default Approach (39 Locations)	
	WAF	Adjustment	WAF	Adjustment
Maximum	0.9288	7.12%	0.9622	3.78%
Minimum	0.9797	2.03%	0.9852	1.48%
Average	0.9601	3.99%	0.9716	2.84%
Median	0.9606	3.95%	0.9698	3.02%

Table 1. 2004 CTM-041 Test Results (75 Total Locations)

Based on a survey conducted as part of the EPRI study it was estimated that rectangular ducts make up about 10% of all Part 75 flow monitoring locations (and tend to be coal-fired, base-loaded units). So, it would appear that there are a substantial number of additional units that could have taken advantage of this method that had not applied a WAF in 2004.

Conclusions/Recommendations

CTM-041 is an effective way to address wall effects when flow is measured in rectangular ducts. Application of the method reduces bias and increases the accuracy of reported emissions. While it would appear that there are a number of sources that have yet to take advantage of it, the method has been successfully implemented by multiple testing companies/utilities a numerous sites.

Much of what was learned in the EPRI Rectangular Duct Wall Effect Study applies not only to rectangular ducts but also to circular stacks. Many of the improvements incorporated in CTM-041 should also be reflected in Method 2H. Changes to Method 2H are recommended to harmonize the two methods. Revisions the method are needed to increase the accuracy of the method and simplify its application:

> <u>Increased Accuracy.</u> The method should require multiple runs but there is no benefit to multi-load testing--do it once but do it right. Unit specific defaults could be used to provide conservative adjustments without testing but still reflect stack size and flow profile characteristics.
>
> <u>Simplified Application.</u> Decoupling the wall effect test method from the RATA and implementing the WAF using a cross-sectional area adjustment approach minimizes unnecessary testing, more equitably applies the correction regardless of the BAF, and simplifies the application of the method.

The benefits to the potential revisions are significant. RMB working to initiate this effort and is soliciting additional utility partners to help fund this work. Based on initial meetings, the Agency appears agreeable to the proposition of revising Method 2H. A supplemental meeting with EMC is planned for later this month to outline a strategy for revising Method 2H to incorporate the improvements in CTM-041 and harmonize the two methods.