Correcting Flow Measurements for Wall Effects in Rectangular Ducts and Stacks

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Summary

The objective of the EPRI Rectangular Duct Wall Effects Study was to evaluate the impact of wall effects in rectangular ducts, with the goal of providing EPA sufficient information to permit wall effects corrections for rectangular ducts. This project was completed last year, and a final report[1] was provided to the Agency. This paper discusses the results of the study, the methodology developed, and some practical aspects of the proposed method.

Introduction

In the 1990's, many utilities discovered that the continuous emissions monitoring systems (CEMS) required under the Acid Rain Program generated heat input and mass emission values that were consistently higher than those determined by more conventional methods. This discrepancy posed significant implications since the Acid Rain Program's emissions accounting framework conveys a monetary value to CEMS data and necessitates precise, accurate measurements. A positive bias in the CEMS measurements translates directly into over-reporting of allowances with millions of dollars of impact that only continues to grow, with the advent of the NO_X Budget trading program and potential CO_2 and Hg trading programs in the future.

To address utility concerns, EPRI undertook a research project that identified and quantified various sources of error in CEMS measurements. Although flow measurement was not the sole culprit, the EPRI study found it to be a significant contributor and that much of the bias was related to the EPA reference method procedures themselves. The discovery of reference method bias was particularly troublesome since these procedures are used to calibrate and certify CEMS flow monitors; thus, any bias associated with the reference method is transferred directly to the stack flow monitor measurements. 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 of the reference method problems that was uncovered in EPRI and EPA studies was the inherent bias that is associated with the equal area traverse procedure. The procedure, specified by Reference Method 1, dictates how stack flow reference traverse points are selected and 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 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.

In 1999, EPA promulgated a number of stack flow reference method revisions including Reference Method 2H, which was designed to address the problems with the equal area traverse procedure. Reference Method 2H allows utilities to perform tests to determine wall-effect adjustment factors for correcting the measured volumetric flow rate. The method also incorporates default correction factors, albeit very conservative ones, that can be used without testing. Unfortunately, Method 2H can currently only be used on circular stacks. No wall-effect corrections are allowed for volumetric flow meters installed on rectangular ducts. However, the same viscous shear wall effect occurs in rectangular ducts. In fact, the wall effect related bias is even more pronounced in rectangular ducts.

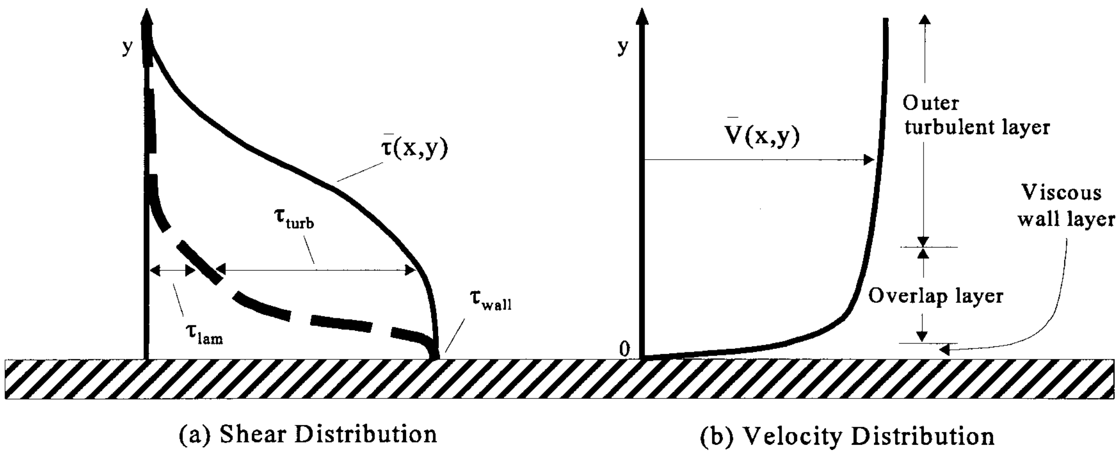

Figure 1. Typical Velocity and Shear Distributions in Turbulent Flow Near a Wall

Intuitively, there are a number of reasons why one would expect that wall effects, i.e., the bias intrinsic to Method 1's equal area technique, would be greater for rectangular ducts than for circular stacks.

– **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.

Because the Acid Rain allowance program is dependent on precise, quantifiable emissions measurements, an inherent bias, such as the one introduced by equal area traverses, should be eliminated. A wall effect adjustment methodology like Method 2H is needed for rectangular ducts. The EPRI Rectangular Duct Wall Effects Study, which was sponsored by several utilities[3], was designed to address that need.

Agency Interaction

The EPRI Rectangular Duct Wall Effects Study, including two very comprehensive field tests, was completed last year, and the final, thoroughly peer-reviewed[4] results and the proposed method were published and provided to EPA in February. During the study, by encouraging and inviting EPA to review and participate in our effort as it progressed, we received reasonable support and cooperation from EPA. Internally within the Agency, the Clean Air Markets Division (CAMD) expressed a desire for the Emission Measurement Center (EMC) to take the lead, suggesting that when EMC was satisfied with the method, then CAMD would readily accept petitions for the method's use.

The Agency suggested that it would post the method on the EMC web site as a conditional test method and that CAMD would respond to petitions for facility-wide pre-approval to use the method. In fact, this approach was outlined in a publicly available document highlighting EMC's activities in 2002[5]:

> **Stack flow rate method to account for wall and corner flow rate effects in rectangular ducts** – We have a current method review project in support of the Clean Air Markets Division (CAMD). The objective is to identify a method suitable for inclusion in alternative method requests by the Part 75 regulated community for flow measurements in rectangular ducts. EPA's current Method 2H, while addressing wall effects in circular ducts, does not address wall and corner equal area flow measurement problems in rectangular ducts. The technical method evaluation field work on this project is being performed by an industry contractor, and we have reviewed this work as it has progressed. The contractor's final report was submitted to us in February 2003; we are coordinating with CAMD to perform a final review of all relevant materials for completeness. If deemed adequate, the method will be placed on our website as a conditional test method (CTM), so it can be used as a common basis for making requests for approval of such an alternative method.

While the utilities expressed a desire to see the method promulgated as a regular EPA test method, the sponsors of the project were agreeable to the conditional test method approach, at least as a first step, since their primary concern was to see a method expeditiously available.

Based on our initial conversations with EMC, RMB expected that the method would have been posted as a conditional test method by now and that this paper would reflect that

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[3] American Electric Power, Southern Company Services, Alliant Energy Corporation, PacifiCorp Electric Operations, and Tennessee Valley Authority

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

[5] *Highlights of the Emissions Measurement Center's Activities for 2003* (sic), March 12, 2003.

conditional test method and, perhaps, the experience of some sources that might have petitioned for its use. However, EPA has not yet released the method as a conditional test method. Months after EPA was provided the EPRI report, EMC seems to be ready to post the method, but CAMD appears to be holding up the process. Based on conversations with EMC, they are now waiting for CAMD to "sign off" on the EPRI report.

While our contract with EPRI for the study has expired, RMB has asked CAMD on a number of occasions regarding the status of the method. Each time, the response has been that reviewing the EPRI report was "on the backburner."

[One thing that CAMD suggested that they would need to address in order to implement the method is how to report the rectangular ducts wall effects test data in the quarterly EDR reports. While we can appreciate that EPA may wish to make some changes to the reporting format, this should not delay the method. The constructs for reporting wall effects test data are already included in the 614, 615, and 616 EDR records[6], and these records are currently written so that they can be used for both circular stacks and rectangular ducts. Also, since near wall point data are not required for Method 2H, it should not be required for the rectangular duct method. Furthermore, the reporting requirements simply do not need to be in place prior to the use of the method. Sources were allowed to use Methods 2G, 2F, and 2H prior to the associated changes in the reporting requirements with the stipulation that the data be maintained on-site. The same approach should be followed again.]

Given the degree of scrutiny that both the field tests and the method were subjected by the peer reviewers and the numerous times the Agency was provided with opportunity to comment during the study, it is not anticipated that the EPA will suggest significant changes to the method prior to posting the method as a conditional test method. Numerous sources would benefit from this method.[7] Perhaps with some encouragement, EPA will make this issue a priority and get the method over this bureaucratic hump.[8]

Wall Effects Theory

A paper presented at the 1998 EPRI CEMS Users Group Meeting[9] discussed the results of a theoretical mathematical model used to determine near wall velocities. The model

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[6] While some minor changes might be made to reflect that, as discussed later in this report, the wall tests are decoupled from the RATA, this would not require significant effort.

[7] In response to a request from the Agency, the EPRI Rectangular Duct Wall Effects Study undertook a survey to determine how many sources would be effected by a wall effects adjustment methodology for rectangular ducts. The survey, which was subject to a wide distribution, suggested that rectangular ducts make up about 10% of all Part 75 flow monitoring locations, with considerable allowance impact since the survey showed that units tend to be coal-fired, base-loaded units.

[8] Particularly since the Agency has been provided with draft results as the study progressed, the final review should be more a simple formality.

[9] Norfleet, Stephen K. *An Evaluation of Wall Effects on Stack Flow Velocities and Related Overestimation Bias in EPA's Stack Flow Reference Methods*, 1998 EPRI CEM Users Group Meeting, New Orleans, Louisiana, May 1998.

was principally based on the well-established work of Millikan who, in 1937, showed that the overlap-layer velocity in turbulent flow applications varies logarithmically with the distance from the wall. The correlation, commonly known as logarithmic law or overlap law, is expressed as:

$$\frac{u}{u^*} = \frac{1}{\kappa} \ln \frac{yu^*}{\nu} + B$$

The logarithmic-overlap law is one of the cornerstones of existing turbulent-shear flow "theory." The Darcy friction factor and the ASME Moody diagram, which serve as the universally accepted foundation for determining design friction for turbulent applications, just represent integrals of the logarithmic-overlap law.

The logarithmic-overlap law can be reduced in two forms, one for fully rough flow and another for hydraulically smooth flow. For hydraulically smooth walls ($\varepsilon u^*/v<5$), there is no effect of roughness and B = 5.0. For fully rough flows ($\varepsilon u^*/v<70$), the sublayer is totally broken up and $B = 8.5-(1/\kappa)\ln(\varepsilon u^*/v)$, causing the viscosity term to vanish. Boiler exhaust flue flows, even in steel stacks or ducts, tend to exhibit fully rough flow or transitory flow characteristics. Given stack/duct construction and the high viscosity of the flue gas, the form of the logarithmic-overlap law most applicable to utility and industrial boiler flues is:

$$\frac{u}{u^*} = \frac{u^*}{0.41} \ln \frac{y}{\varepsilon} + 8.5$$

where,

u	=	velocity of near wall measurement
u^*	=	friction velocity, $(\tau_w /\rho)^{1/2}$
y	=	distance from wall
ε	=	wall roughness

The equations tell us that the wall effects are independent of Reynolds number, which in practical terms means that the wall effects are independent of both velocity and viscosity. Stated simply, test data and flow theory indicate that there is no need for testing at different loads.

The 1998 CEMS Users Group Meeting paper showed that the logarithmic law-based theoretical model provided very accurate characterizations of near wall velocity profiles. Excellent agreement was demonstrated between the model and actual measurements from both the EPRI and EPA flow study field tests. The performance of the model was not surprising since the effectiveness and accuracy of the logarithmic overlap law has been firmly established and tested over a wide range of conditions for over 60 years.

Wall Effects Correction Method

As part of this study, a measurement-based reference method to calculate the wall effect adjustment factors for rectangular ducts was developed. The rectangular duct wall effect reference method procedures were developed following the same general approach as used in Method 2H.

Under Method 2H, 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. The 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).[10]

Applying an identical numerical integration to a rectangular duct, the wall effects adjusted (replacement) velocity for the non-corner exterior equal-area sectors along the test port wall can be defined by the following equation:

$$\hat{v}_x = \frac{\left[\frac{0+v_1}{2}(1")\left(d_{b_y}\right) + \frac{v_1+v_2}{2}(1")\left(d_{b_y}\right) + \frac{v_2+v_3}{2}(1")\left(d_{b_y}\right) \cdots + \frac{v_{last-1}+v_{last}}{2}(1")\left(d_{b_y}\right) + v_{dremx}\left(d_{b_x} - d_{last}\right)\left(d_{b_y}\right)\right]}{\left(d_{b_x}\right)\left(d_{b_y}\right)}$$

where,

$\hat{v}_x$	=	wall effects adjusted velocity for the exterior equal-area sectors along the test port wall and the opposite wall, ft/s
v_i	=	velocity measured at the i^{th} one-inch interval from the test port wall, ft/s
v_{dremx}	=	velocity measured at the mid-point between d_{last} and the interior edge of the Method 1 equal-area sector closest to the wall, ft/s
d_{b_x}	=	distance from the test port wall to boundary of equal area, in.
d_{b_y}	=	distance from the adjacent wall to boundary of equal area, in.
d_{last}	=	distance from the test port wall of the last one-inch interval velocity measurement, in.

Which can be reduced to:

[10] 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.

$$\hat{v}_x = \frac{\left[\sum_{d=1}^{d_{last}-1}(v_d) + \frac{v_{last}}{2} + v_{dremx}(d_{bx} - d_{last})\right]}{d_{b_x}}$$

For the corner exterior equal-area sectors along the test port wall, the geometry is different, and the wall effects adjusted (replacement) velocity that accounts for wall effects, but not the impact of the more intense shear in the corners, can be defined as follows:

$$\hat{v}_c = \frac{\left[\begin{array}{l}\frac{0+v_1}{2}\left(d_{b_x} + d_{b_y} - 1\right) + \frac{v_1+v_2}{2}\left(d_{b_x} + d_{b_y} - 3\right) + \frac{v_2+v_3}{2}\left(d_{b_x} + d_{b_y} - 5\right) + \cdots \\ + \frac{v_{last-1}+v_{last}}{2}\left(d_{b_x} + d_{b_y} - (2d_{last} - 1)\right) + v_{drem_c}\left(d_{b_x} - d_{last}\right)\left(d_{b_y} - d_{last}\right)\end{array}\right]}{d_{b_x} d_{b_y}}$$

where,

$\hat{v}_c$	=	wall effects adjusted velocity for the corner equal-area sectors, ft/s
v_{dremc}	=	velocity measured a point representing the centroid of the area between d_{last} and the interior edge of the corner Method 1 equal-area sector closest to the wall, ft/s

which can be reduced to:

$$\hat{v}_c = \frac{\sum_{d=1}^{d_{last}}\left[\left(\frac{v_{d-1}+v_d}{2}\right)\left(d_{b_x} + d_{b_y} - 2d + 1\right)\right] + v_{drem_c}\left(d_{b_x} - d_{last}\right)\left(d_{b_y} - d_{last}\right)}{d_{b_x} d_{b_y}}$$

Such an approach can be used to determine the wall effects for the equal areas adjacent to the test port wall. But, as previously stated, it is not practical or even possible to make measurements from all four sides of the duct in most situations. So, an approach is needed that can be used to translate the wall effects measured at one wall to correct the data for the exterior equal-areas along the other walls.

The impact of wall effects on flow remains relatively consistent across a stack, and the overall effect is a function of the average roughness; in other words, the near-wall profiles tend to exhibit the same shape. This tendency means that, while the bulk velocity may vary from equal-area to equal-area, the ratio of velocities at given points from the wall will tend not to vary. Thus, while near-wall measurements cannot be made at each Method 1 equal area near the walls in a rectangular duct, the average impact of the roughness of the duct walls that is categorized at each port can be used to correct the flow at the other near wall regions. At its core, this is exactly what is being done for circular stacks in Method 2H, where the near-wall flow profile at the four port locations is taken to be representative of the entire stack wall region.

An average near-wall velocity profile serves as a useful construct in allowing us to apply the wall effects characterization gleaned from the near wall measurements. An appreciation of the underlying viscous shear phenomenon as well as the growing library of near wall measurement data show that while the velocities measured at each test port may differ, the profile (or slope) of the near-wall velocities at each port will be similar. The profile similarity is an outgrowth of the similarity in wall roughness for a given stack or duct cross-section.

The similarity means that, if the average profile at a number of locations on the stack or duct wall is known, the velocities can be scaled at other points along the wall. The near-wall velocities can be reduced to a function of the velocity of an analogous point measured near the wall. One can take the measurements at some near wall locations and apply the information to other locations along the wall.

To translate the results to the other equal areas along the perimeter, the wall effects adjusted velocities, (both $\hat{v}_x$ and $\hat{v}_c$) will be calculated based on measurements at each test port location. Since the distances d_{b_x} and d_{b_y} may not be the same, the distance of the nearest exterior Method 1 traverse points from the test port wall (and the centroid of any remainder portion) may be different than for the equal areas nearest the perpendicular walls. Thus, wall effects velocities will also be calculated based on the geometry of the exterior equal area sectors along the walls that are perpendicular to the test port wall:

$$\hat{v}_y = \frac{\left[\sum_{d=1}^{d_{last}-1} (v_d) + \frac{v_{last}}{2} + v_{dremy}\left(d_{b\,y} - d_{last}\right)\right]}{d_{b_y}}$$

where,

$\hat{v}_y$	=	wall effects adjusted velocity for the exterior equal-area sectors along the walls adjacent to the test port wall, ft/s
v_{dremy}	=	velocity measured a point representing the mid-point between d_{last} and d_{b_y}, ft/s

The ratio of the wall affect adjusted velocities ($\hat{v}_x$, $\hat{v}_y$, and $\hat{v}_c$) to the velocities measured at the respective Method 1 traverse point distances will be determined for each traverse port location. Correction factors for each exterior equal area type (wall sectors along the test wall or opposite wall, wall sectors on walls perpendicular to the test port wall, and corner sectors)[11] will be calculated by averaging the respective ratios from all test port locations:

[11] The method also includes similarly developed correction factors that can be used to account for potential geometry differences due to an ash layer.

$$C_x = \frac{\sum_{j=1}^{n_x} \left(\frac{\hat{v}_x}{v_x} \right)_j}{n_x} \quad C_y = \frac{\sum_{j=1}^{n_x} \left(\frac{\hat{v}_y}{v_y} \right)_j}{n_x} \quad C^*_c = \frac{\sum_{j=1}^{n_x} \left(\frac{\hat{v}_c}{v_c} \right)_j}{n_x}$$

where,

C_x	=	wall effects adjustment factor for non-corner, exterior equal-area sectors adjacent to the test port wall and opposing wall
C_y	=	wall effects adjustment factor non-corner, exterior equal-area sectors adjacent to the walls perpendicular to the test port wall
C^*_c	=	wall effects adjustment factor for corner equal-area sectors that excludes the impact of greater intense shear in the duct corners
n_x	=	number of tests ports traversed

The unadjusted Method 1 traverse point velocity will then be multiplied times the appropriate correction factors (with the corner correction factor adjusted for the more intense shear in the corners based on the findings of this study) to calculate the wall effects adjusted for each exterior equal area. A side benefit of the use of the averaged correction factors is that it will help normalize the uncertainties associated with the wall effects measurements at any given port.

$$\hat{v}_i = v_i \times C_i$$

As with Method 2H, a WAF for the entire cross-section can be calculated by dividing the average stack gas velocity adjusted for wall effects by the average unadjusted velocity:

$$WAF = \frac{\hat{v}_{avg}}{v_{avg}}$$

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[12] 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:

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

where,

Q_{adj}	=	wall effects adjusted volumetric stack flow, scf/s

[12] 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.

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

Field Test Locations

Field tests were conducted at two representative utility monitoring locations. Tests were performed at Southwestern Electric Power Company's Welsh Generating Station Unit 1, which is an opposed-wall, coal-fired dry bottom boiler that has a nameplate generating capacity of 558 megawatts (MW). The test location was on a vertical, rectangular stack with a cross section of 12' x 18.5'. A diagram of the test location is shown in Figure 2.

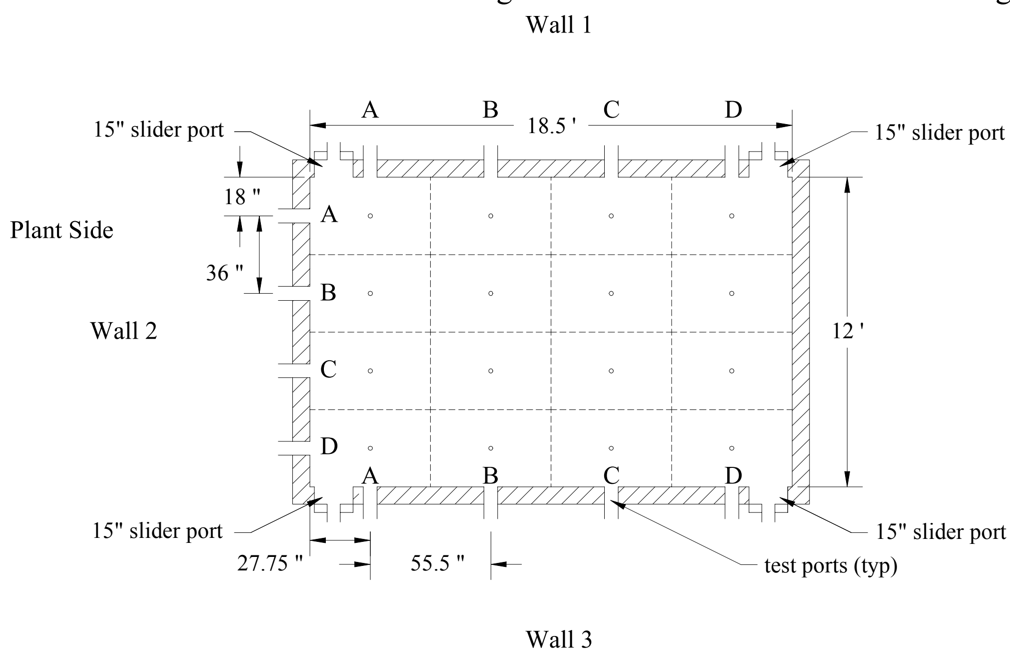

Figure 2. Welsh Unit 1 Test Location

The second set of tests was conducted at Gulf Power Company's Crist Generating Station Unit 5, which is a tangentially-fired coal boiler that has a nameplate generating capacity of 75 MW. The main test location was downstream of the Unit 5 induced draft (ID) fans in a straight horizontal duct section with a cross section of 7.3" x 12.7". A diagram of the test location is shown in Figure 3.

[13] 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.

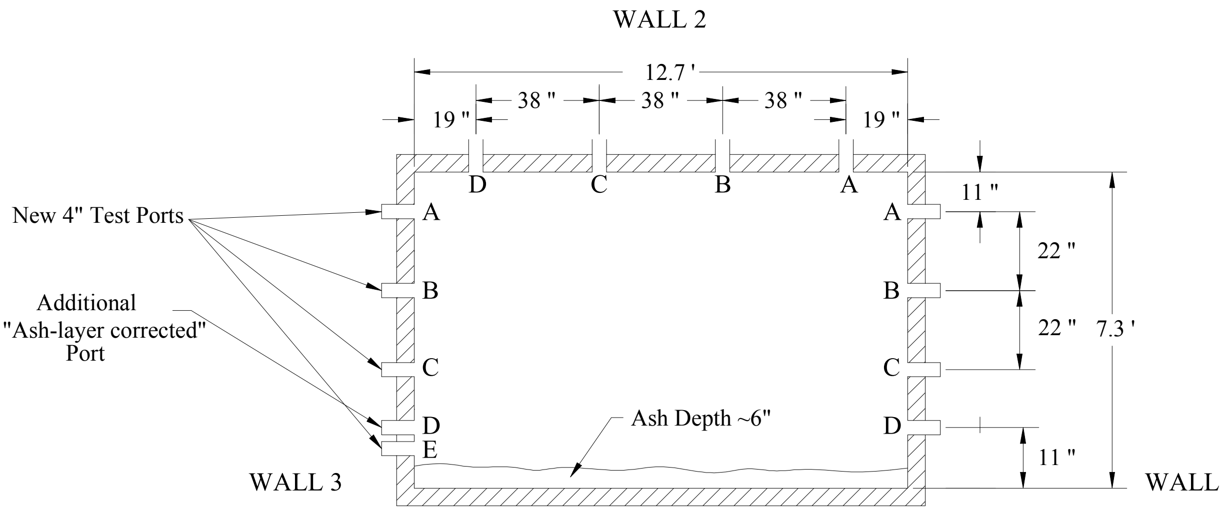

Figure 3. Crist Unit 5 Test Location

At both the Welsh and Crist test sites, there were ample straight duct/stack runs prior to the measurement locations where the flow was not affected by bulk disturbances. However, at each site there were, typical to flue ductwork, periodic cross-bracings that did need to be taken into consideration.

Field Test Program Design

Peer-reviewed, site-specific test plans were developed for the Welsh and Crist tests. 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.[14] 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:

<u>Testing from Multiple Walls.</u> The velocity decay at the wall and corners of the duct is a manifestation of a viscous shear phenomenon that is dependent on stack or duct geometry and wall roughness. Under Reference Method 2H, the wall effects are categorized by making near wall measurements at each test port location. The impact of the wall roughness for the entire cross-section is approximated based on measurements at four locations.

A similar approach is envisioned for rectangular ducts. Under the proposed test method, the wall effects for the entire cross-section in rectangular ducts will be categorized based on near wall measurements taken near the wall at each of the Method 1 traverse ports.

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

Unlike a circular stack, however, a traverse port will not be found at all the Method 1 equal areas that border the stack or duct wall. On rectangular ducts, Method 1 only requires that test ports be located along one wall of the duct; and it is impractical, and many times impossible, to install test ports or make flow measurements from all four walls.

But, while near-wall measurements cannot be made at each Method 1 equal area near the walls in a rectangular duct, the average impact of the roughness of the duct walls that is categorized at each port can be used to correct the flow at the other near wall regions. In fact, in many ducts, the wall roughness impact can be more fully categorized than it is in circular stacks because there are more ports from which to take near-wall measurements.

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[15], 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."[16] 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. Slider ports were installed in all four corners at the Welsh and in the two top corners at Crist within the proximity of the test port plane.

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.

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[15] 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.

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

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.

Field Test Results

Tests Completed. At Welsh, 12 autoprobe wall effects runs were performed using both Reference Method 2 and 2G for each of the three available walls. Seven to eight manual Reference Method 2 wall effects runs were performed for each wall during the same time period. At Crist, test plan modifications[17] allowed for a significant increase in the amount of wall effect data collected. Over 20 autoprobe and 12 manual Method 2 wall effects runs were performed for each of the available walls at Crist. Three sets of corner traverses were performed in the corners at both stations.

Wall Effects Results. The Welsh and Crist data demonstrated good repeatability and agreement between WAF values calculated from wall-to-wall.[18] Very good agreement was seen between the measured near wall velocities and those modeled based on the fluid dynamic principles. Table 1 summarizes the results of the wall effects tests at both sites. The average WAF value, including the impact of the more intense viscous shear effects in the corners as determined from the corner tests, was 0.9592 (4.08%) at Welsh and 0.9457 (5.43%) at Crist 5. While there was a significant amount of port-to-port variation at Crist 5, the variation did not appear to have significant impact when the results were averaged together for each wall.

Table 1. Wall-Effects Test Results Summary (Autoprobe Average)

	WAF Value				Port-to-Port WAF St. Dev.
	Wall 1	Wall 2	Wall 3	Average	
Welsh 1	0.9600 (4.00%)	0.9573 (4.27%)	0.9603 (3.97%)	0.9592 (4.08%)	0.0030 (0.30%)
Crist 5	0.9461 (5.39%)	0.9483 (5.17%)	0.9426 (5.74%)	0.9457 (5.43%)	0.0216 (2.16%)

Highlights of Study Results and Method Application

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:

[17] In particular, Method 2G autoprobe runs were dropped since little swirl was seen and since no differences were seen in the WAF values calculated based on either method at Welsh.
[18] The data for Ports A and D on Walls 1 and 3 at both sites at both stations were excluded due to the presence of cross-bracing, which impacted the measurements in the near wall region, critical to the WAF calculations. Intersections further from the wall appear to have had little influence on the measurements.

- 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[19], in.
d = distance d from wall, in.

The inherent conservative nature of the duct specific default approach is illustrated in Figure 3.

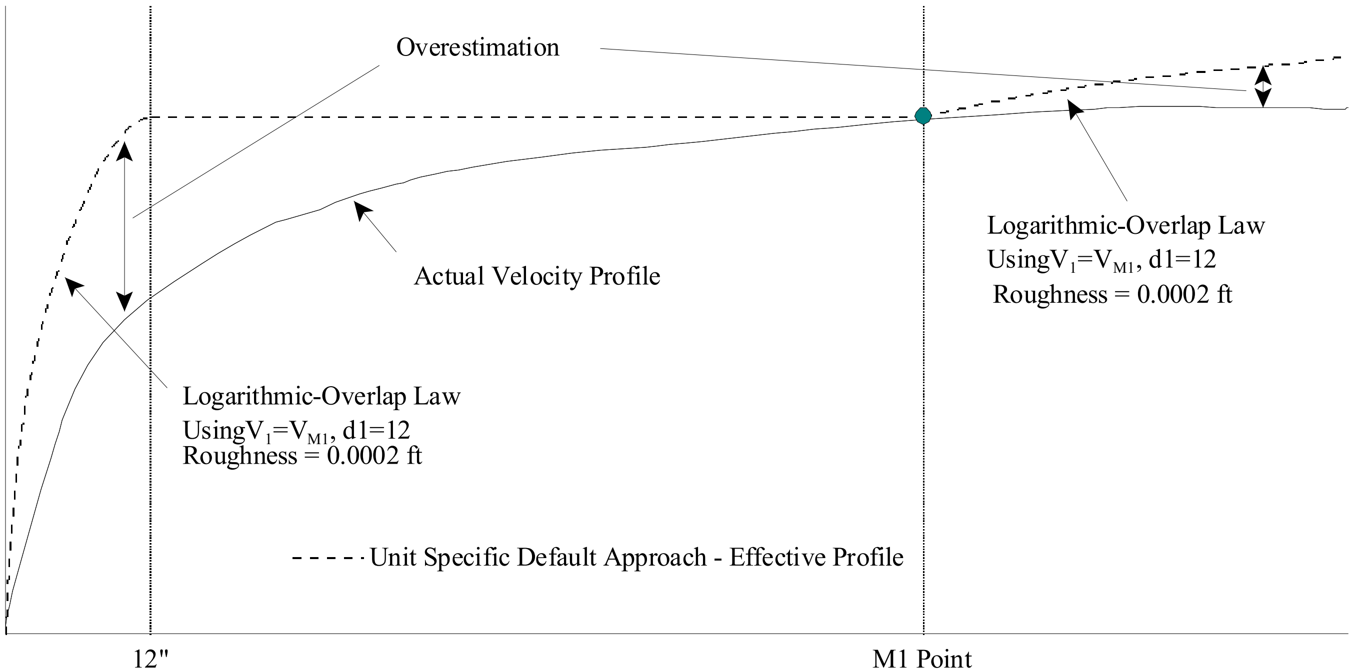

Figure 3. Duct Specific Default Approach

- 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

[19] 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.

- 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.[20] Measurements from at least four ports seem necessary based on the results at Crist and the wall effects test data reported for circular stacks.

Conclusions

In order to report emissions more accurately, a wall effect adjustment methodology is needed for rectangular ducts. The method developed under the EPRI Rectangular Ducts Wall Effects Study is a viable, field tested method that was subject to thorough peer review. The method will increase the accuracy of the emissions reported at rectangular duct monitoring locations and should be promptly addressed by EPA. Furthermore, many of the conclusions of the study apply not only to rectangular ducts but also to circular stacks, so changes to EPA Reference Method 2H are also recommended.

[20] 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.