Techniques to Improve Measurement Accuracy in Power Plant Reported Emissions

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ABSTRACT

Utilities in the U.S. with fossil-fired power plants are required to use continuous emissions monitoring systems (CEMs) to measure and report quantities such as NO_x and SO_2 emissions. Among its many components, the typical, most used CEM system includes a flue gas flow meter and a device referred to as a dilution extractive probe for flue gas sampling. Numerous studies have pointed to positive measurement bias errors in these devices which can be as high as 20 percent in some cases. Over-reporting represents the potential for financial losses associated with the NO_x and SO_2 emissions trading system in the U.S.

This paper reports work performed by the Lehigh University Energy Research Center on flow measurement and dilution probe accuracy issues and describes approaches which have been developed to improve measurement performance of stack flow instrumentation and dilution extractive probes. Case studies are presented on the implementation of these approaches to utility stacks which have resulted in emissions over-reporting reductions in excess of 15 percent. A case study on the use of Computational Fluid Dynamics (CFD) to guide the design of modifications to existing stacks and improve CEM measurement accuracy is illustrated. In this study, the flue gas flow at the exit of a heat recovery steam generator (HRSG) through stack was modeled and various design alternatives were investigated to determine optimum piping configuration and CEM system location. Another result of the ERC work, presented here, is hardware and software (a correction algorithm) modifications to the standard dilution extractive probe system which compensates for instantaneous changes in probe accuracy due to variations in stack and probe operating conditions.

INTRODUCTION

As part of the process of reporting emissions of NO_x and SO_2 to comply with federal and state clean air regulatory requirements, U.S. utilities are required to use continuous emissions monitoring systems (CEMs) to measure and calculate mass pollutant emissions. To do this, a CEM system needs an instrument to measure flue gas flow rate, instruments to measure concentrations of NO_x, SO_2 and CO_2 (or O_2) in the flue gas and, typically, a device referred to as a dilution extractive probe for flue gas sampling. The dilution probe conditions the sample and transports it to the gas analyzers for measurement of flue gas composition. Errors arise from the inaccuracies in the equipment used to measure flue gas flow rates, pollutant concentrations and in the dilution probe system. Strict calibration procedures are used to reduce errors resulting from gas analyzer measurement accuracies. In some cases, corrections are introduced to reduce the effect of barometric pressure on certain analyzer readings.

Over the last several years, considerable attention has been given to the accuracy of CEM measurements. Power generation companies are concerned with meeting applicable measurement standards, as well as avoiding over-reporting emissions. Numerous studies[1] reported evidence that the procedures specified in the EPA regulations for certifying the accuracies of flow monitors result in measured gas flow rates which are higher than the actual values. This resulted in modifications to the EPA regulations which permit utilities to use more accurate equipment and procedures for calibrating flow monitors. In the case of the dilution probe system, several investigators[2] have reported on the limitations or inherent problems associated with the dilution probe which result in positive measurement bias errors. These errors are caused by changes in stack conditions and dilution probe operating conditions. Changes in stack and probe operating conditions result in changes in the extracted sample that are not compensated by the system’s components.

This paper reports work performed by the Energy Research Center (ERC) on flow measurement and dilution probe accuracy issues and describes approaches which have been developed to improve measurement performance of stack flow instrumentation and dilution extractive probes. The use of a computational tool to guide design indications of existing stacks and the investigation of alternatives for optimal CEM system location and configuration is also reported.

STACK FLOW MEASUREMENT ACCURACY

The flow rate of flue gas in a stack is measured continuously by a flow monitor. Periodic calibrations of the equipment are mandated by the U.S. EPA to ensure accurate flow measurement. EPA regulations stipulate the frequency of calibrations, as well as the equipment and procedures used for equipment calibration and certification. Up until the Summer of 1999, EPA procedures mandated the use of an S-probe in the straight up mode, and use of the Equal Area Method (EAM) to convert probe readings into information on flow rate.

After calibrating flow monitors in accord with these EPA requirements, utilities found their CEM flow instruments indicating stack flue gas flow rates which were significantly (up to 20 percent) higher than the actual flows. The flow measurement accuracy studies that followed traced these positive flow bias errors to the S-probe design, use of default value of probe calibration coefficient C_p, use of the EAM, and errors in measurement of velocity head.

The flow in a power plant stack is typically non axial, often with large tangential and radial components (Figure 1). Due to its design, the S-probe is sensing a velocity head which corresponds to the total flow velocity. Since the total flow velocity is larger than its axial component (which is needed to determine the flow rate), the use of a S-Probe in non-axial flows results in a higher than actual flow rate. This has been experimentally documented by several authors. The S-Probe error, determined by the ERC and EPRI, is presented in Figure 2 as a function of the average resultant angle. The resultant angle (RA), as defined by EPA, is a measure of flow obliqueness. For axial flows RA is zero, while the non-zero values of RA indicate oblique flow. The results from Figure 2 show that the S-Probe error is a strong function of flow obliqueness. A part of the positive flow bias error, associated with the S-probe, is due to the use of a default value of probe calibration coefficient which is higher than the actual value. A comparison of the actual and default values of C_p, presented in Figure 3, shows default value being almost 2 percent higher compared to the actual C_p value. For the accurate flow measurement it is, therefore, important to use properly calibrated probes.

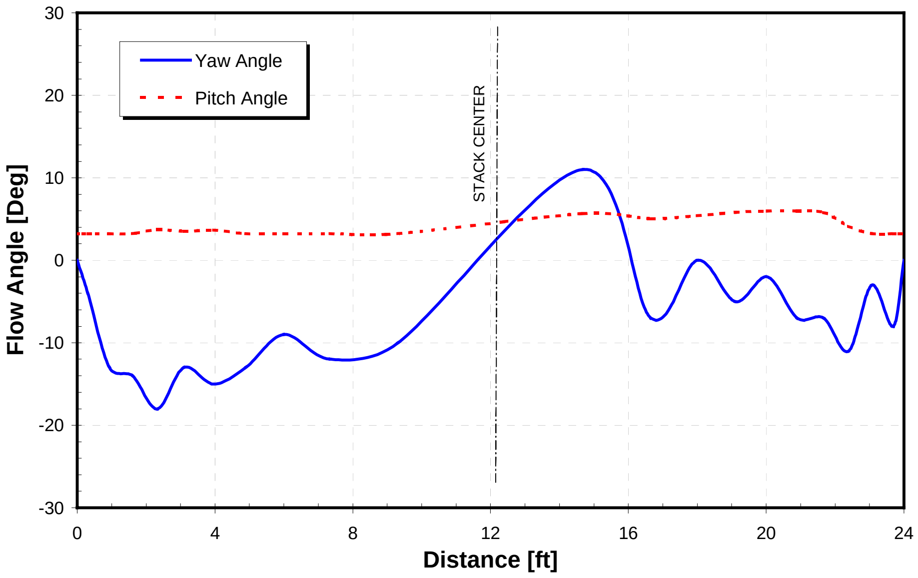

FIGURE 1 – TYPICAL NON-AXIAL FLOW IN POWER PLANT STACK

The flue gas flow rate, required for flow monitor calibration, is determined by traversing stack cross sectional area along the two mutually perpendicular stack diameters and obtaining probe readings at each traverse point. A typical axial flow velocity profile, measured along stack diameter, is presented in Figure 4. The EAM is then used to convert traverse data into the flow rate. This method is subject to the two types of errors: calculation method and discretization errors.

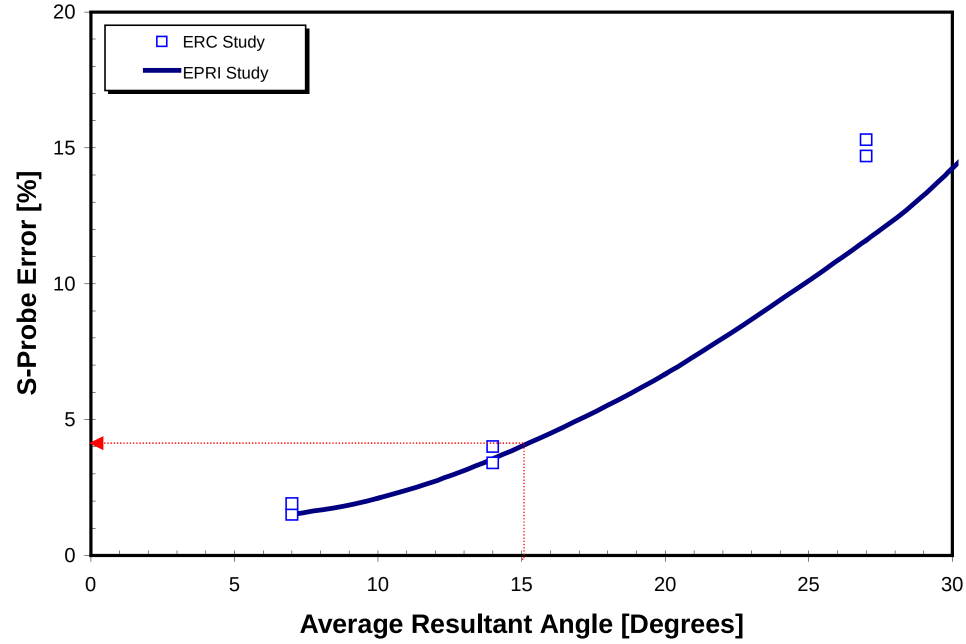

FIGURE 2 – S-PROBE ERROR AS A FUNCTION OF AVERAGE RESULTANT ANGLE

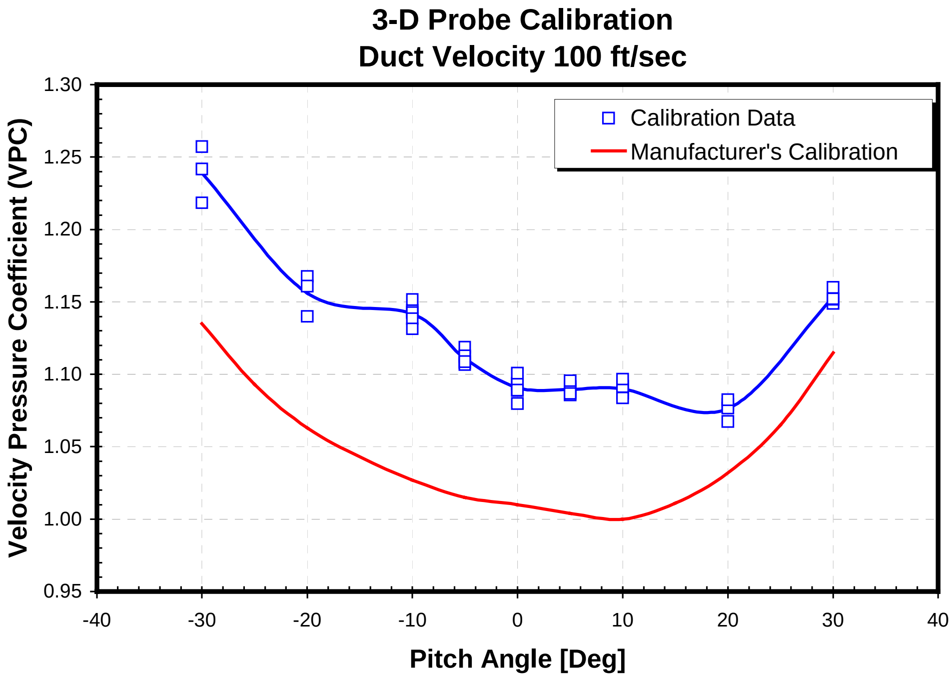

FIGURE 3 – VPC DATA FOR 3-D PROBE CALIBRATION

The calculation method error is due to the fact that EAM ignores the no slip wall boundary condition. As a consequence, the calculated flow rate is typically biased 1 to 2 percent high compared to the true flow. (The true flow is determined by curve-fitting and integrating the measured axial velocity profile.) The shaded triangles in Figure 4 illustrate the magnitude of flow overestimation by the EAM.

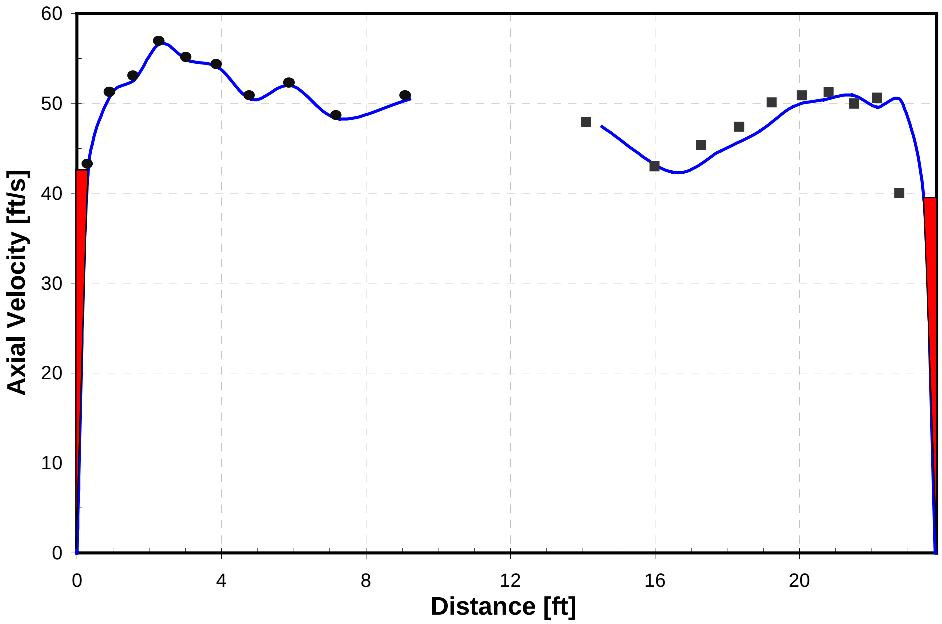

FIGURE 4 – TYPICAL STACK AXIAL FLOW VELOCITY PROFILE

The discretization error is due to the fact that, in stack traverse, the actual flow velocity profile is represented by a limited number of traverse data points. As the number of traverse points is increased, i.e., as the flow velocity profile is more accurately defined, discretization error decreases. This is shown in Figure 5 where discretization error is plotted as a function of a number of traverse data points. For a coarse grid of 12 traverse points, discretization error is close to one percent. As the number of traverse points is increased, discretization error decreases and levels off after the optimal number of traverse points (in this case 24) is exceeded.

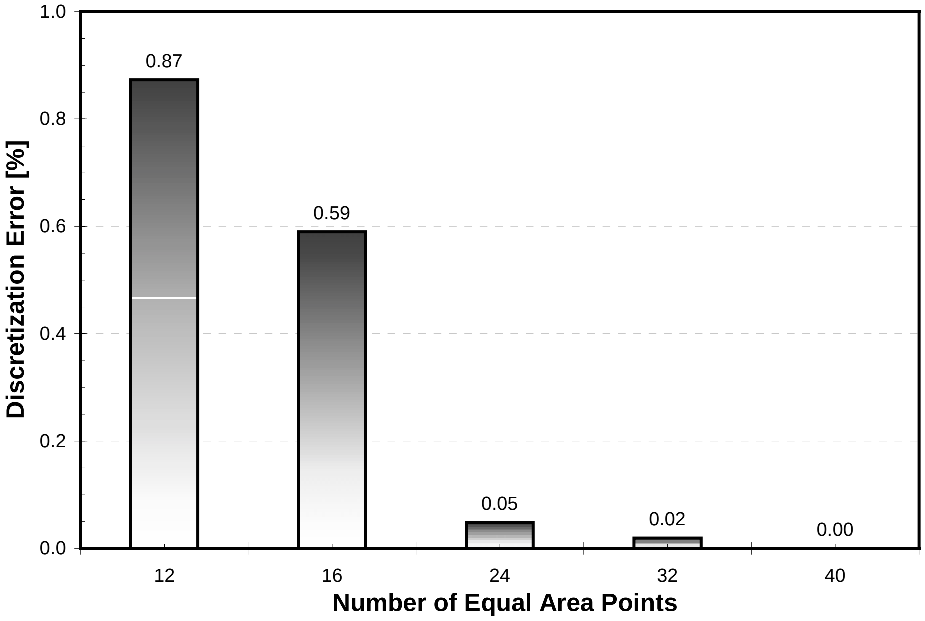

FIGURE 5 – EAM DISCRETIZATION ERROR AS A FUNCTION OF NUMBER OF TRAVERSE POINTS

It has to be noted that the magnitude of the calculation and discretization errors and the optimal number of traverse points are highly site-specific and depend on parameters such as; stack and breeching geometry, flow velocity profile, stack wall roughness and other.

In response to the industry criticism, after conducting an extensive field study, EPA has, in Summer of 1999, updated its Flow Reference Methods and calculation procedures. The new methods and procedures allow yaw-nulling of a S-Probe, use of a three-dimensional probe, and application of a wall correction factor to the EAM. Yaw-nulling allows determination of the tangential flow component (the radial component is not determined) and, therefore, reduces the S-Probe error. Use of a 3-D probe allows determination of all three velocity components and eliminates the S-Probe error. Use of a wall correction factor decreases or eliminates the flow calculation error.

New EPA regulations in conjunction with carefully planned and performed stack traverses, application of advanced instrumentation for velocity head measurement, use of calibrated velocity probes, and automated analysis of test data have resulted in a significant reduction in flow bias error. The reductions in flow bias error, achievable with old EPA regulations, are much smaller and are presented for comparison. The authors believe the residual flow bias error is in the 1 to 2 percent range. This error is primarily due to the uncertainty in probe calibration, and use of long elastic probes that flex in highly turbulent stack flow. The makeup of the flow bias error, determined at four utility stacks, is shown in Figure 6.

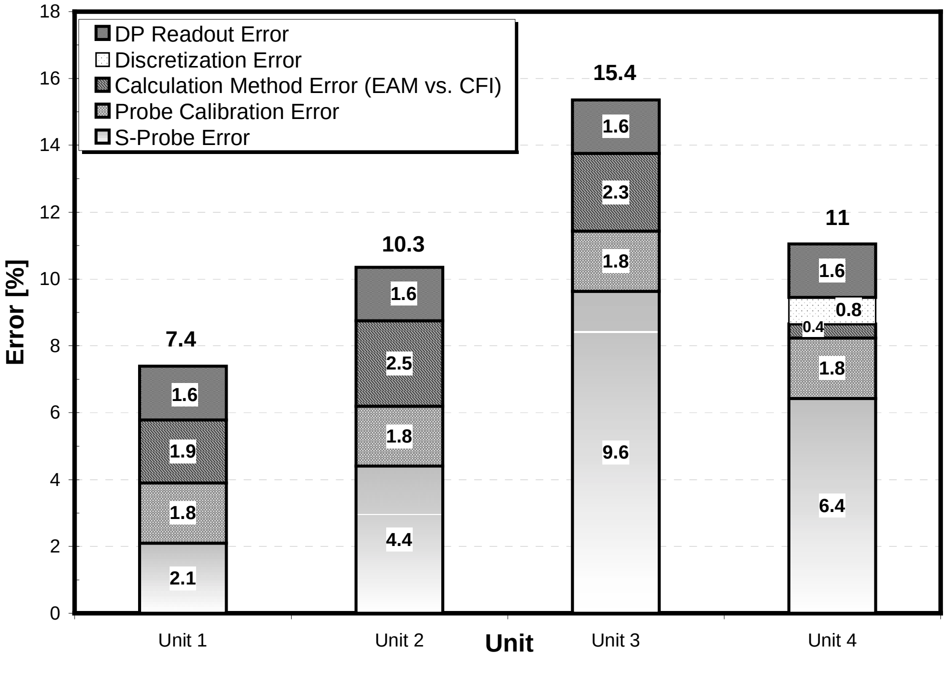

FIGURE 6 – ERROR CONTRIBUTION IN STACK FLOW MEASUREMENT

DILUTION PROBE SAMPLING ACCURACY

The extractive dilution probe system is one of the most widely used for stack gas extraction and sample conditioning. The main advantage of the dilution probe system is that it dilutes the sample to clean and dry it, working at sampling rates significantly less than source-level systems and directly measuring gas concentration on a wet basis. During normal operation, gas from the stack is drawn into the probe, mixed with clean, dry air and then sent to the gas analyzers in a diluted form. Data obtained from the analyzers are converted to the source or stack level concentration by multiplying the analyzer reading by the dilution ratio (ratio of dilution air flow rate to sample gas flow rate). The relationship between the actual pollutant concentration at the stack and the pollutant level measured at the analyzers is constant if the dilution ratio does not change over time. In practice, however, the dilution ratio determined at calibration conditions will differ from when the system is in the sampling mode. There are many factors that affect dilution ratio flow rate and sample flow rate. These include, for example, stack temperature and absolute pressure, flue gas molecular weight and dilution air supply pressure and temperature.

A previous study performed by the authors[3] determined that the effect of stack pressure is linear and corresponds to approximately a 0.25 percent difference in reading for a 1.0 in.w.g. change in absolute pressure. The effect of stack temperature is nonlinear and asymmetric with respect to baseline temperature. This effect is due to the changes in sample gas flow and dilution air flow caused by changes in stack temperature. The temperature effect causes a 1 percent increase in the dilution ratio error for approximately a 60°F drop in temperature. For a typical range of economizer excess O_2 (2 to 6 percent), the effect of sample gas molecular weight represents an error in dilution ratio of the order of 0.5 percent. The effect of dilution air pressure on probe accuracy might be considerable, depending on the precision of the control of the dilution air line pressure. For a regulator pressure of 50 psig, a ± 1 percent change in dilution air pressure will translate into approximately ± 0.75 percent error in the dilution ratio.

The ERC and PPL Generation performed a study to investigate the source of dilution probe errors and according to the results of this study, developed a method to compensate for instantaneous changes in dilution ratio due to variations in operating conditions in the stack and dilution probe system. The study consisted of computer simulations and engineering analysis of the fluid flow and transfer processes occurring within the probe which looked at the factors that affect the flow rates of dilution air, sample gas flow rate and the flow rate of calibration gas. Error propagation and sensitivity analyses were performed to quantify the relative magnitude of the different probe errors. Experiments were also run at controlled conditions in a PPL test facility to measure the dependence of dilution ratio on parameters such as sample molecular weight and dilution air supply pressure. Comparisons were also made to laboratory test data that had been published by EPRI several year earlier[4]. The results of the computer simulations and experiments showed some of the factors that affect dilution ratio can be calculated from firs-principles quite accurately. However, there are other effects that are difficult to tackle with much precision, due to uncertainties in internal probe dimensions and probe assembly.

Based on the results of the referred study, the ERC and PPL Generation developed modifications to the standard dilution extractive probe system which consist of a combination of direct measurements of probe-operating conditions (by means of hardware upgrades) and theoretically derived algorithms. These modifications were based on a new definition of the dilution ratio, expressed in terms of mass flow rates. Additional laboratory tests performed at the PPL test facility showed that the improved system resulted in excellent agreement between measured sample gas composition and actual values of gas composition. Figure 7 shows the results of an evaluation for the compensation of the effect of sample gas temperature on the dilution ratio and the consequent reported emission concentration. The measured stagnation temperature, which represents an indication of the temperature of the gas flowing through the front of the probe under the sampling mode, was used to correlate the data. Two gas mixtures, corresponding to high- and mid-span were used. The results for all measured species indicate that the uncorrected concentration percent error can reach a range of -9.0 to -13.0 percent for an increase in temperature (from baseline conditions) of approximately 330°F. For the operating range of the parameters tested in these experiments, the average error given by the modified dilution probe system was between -1.381 and +0.948 percent for NO_x, SO_2 and CO_2, respectively. For the three pollutants, the correction algorithm was able to maintain a fairly constant reported output for the range of temperatures from ambient to approximately 385°F.

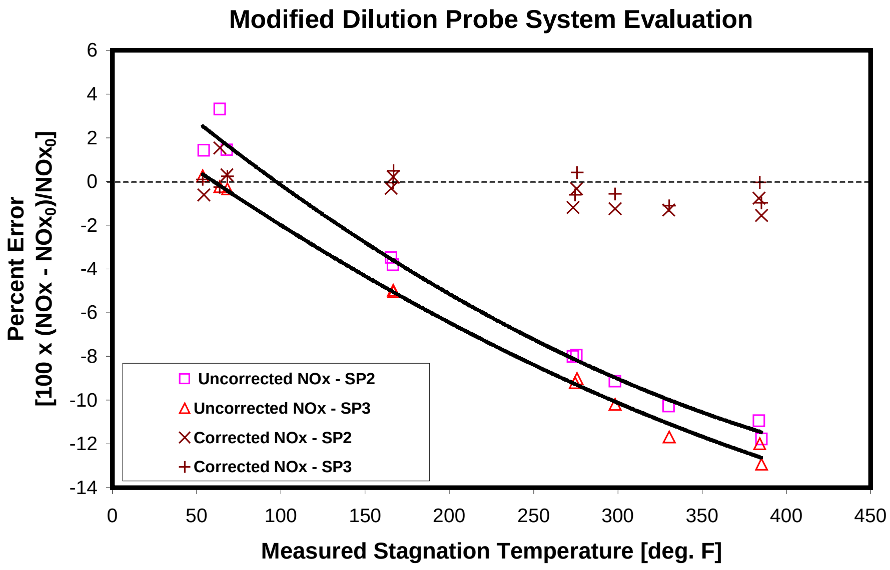

FIGURE 7 – EFFECT OF SAMPLE GAS TEMPERATURE ON NO_x

The dilution probe modifications were incorporated into a new Dilution Ratio Calculation System (a patent is pending for the method used to calculate the dilution ratio[5]) which is being commercialized through a technology referred to as **DRCalc™**. The details of **DRCalc™** system are given elsewhere[5].

PPL Generation has implemented **DRCalc™** on all its fossil-fired units (more than 5,000 MW of installed fossil-fired capacity monitored by CEMs with the dilution probe modifications), taking the steps necessary to ensure the modifications met the quality assurance requirements of the CEMs regulations. Evaluation of the results of these implementations showed a range of percent differences between the uncorrected reported NO_x and SO_2 tonnage (using a constant dilution ratio) and the corrected NO_x and SO_2 from 3 to 9 percent. Figure 8 presents the results of the comparison for four of the largest PPL Corporation's stacks. These units range in capacity from 300 MW (Stack A) to 750 MW

(Stack D). The comparison periods ranged between 2 to 3 months. For the four stacks compared, the corrected reported NO_x tonnage was consistently lower than when no correction was applied. The estimated average cumulative number of NO_x credits over-reported in a month period by the unmodified dilution probe systems ranged between 9 to approximately 65 tons. SO_2 was also in error by a comparable percentage.

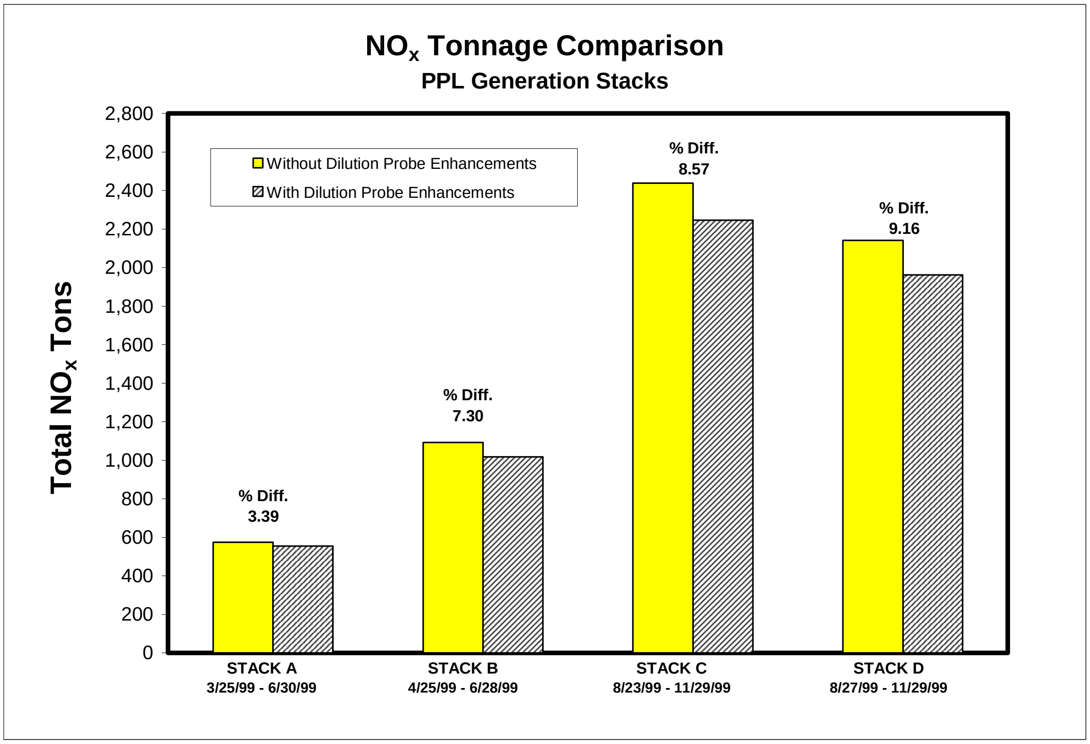

FIGURE 8 – COMPARISON OF REPORTED NO_x TONNAGE FOR DIFFERENT PPL GENERATION STACKS

THE USE OF CFD TO DETERMINE CEMs LOCATION

Design modifications to an existing stack and the optimal location of a CEM system were evaluated using a Computational Fluid Dynamic (CFD) software (CFX 4-4). An existing stack used for exhaust gases from package boilers was modified to discharge the exhaust gases from a heat recovery regeneration system (HRSG), since a Northeast state did not allow installing another stack. Due to the space constraints, the ducts that connect the HRSG exhaust gases to the existing stack do not have long runs for the flow to become uniform or well mixed before the CEM location. Figure 9 illustrates the geometry of the stack with ducts from the HRSG exit and possible CEM locations as proposed by plant. Three-dimensional CFD simulations were performed with the CFX-4.3 software developed by AEA technology[6]. The numerical simulations were performed by solving a set of time averaged Navier-Stokes equations together with a k-ε turbulence model and isotropic eddy viscosity assumption, which relates the Reynolds stress linearly to the mean velocity gradient. CFX-4 uses the finite volume method and body-fitted coordinate formulation with a non-staggered grid arrangement. The solutions were assumed to be converged when the normalized sum of all residuals were less than 10^{-4}. The calculation domain was discretized with approximately 100,000 computational cells as a result of a grid independence study.

The CFD simulation results for the originally proposed geometry indicated severe flow stratifications in both the vertical and horizontal ducts. The results for velocity field is shown in Figure 10 for the original geometry proposed by the vendor. As can be seen from Figure 10, the installation of CEMs in either location of the duct would result in measurement errors due to severe flow stratifications. A number of design options were investigated with CFD software. These included a mixing box to replace the first elbow in the configuration, insertions pieces inside the elbow (to eliminate the circulation in the inner elbow), and guided vanes inserted in the first elbow. The flow patterns and turbulence levels at the possible measurement planes were compared between these geometries. In addition, pressure drop characteristics of each modification were also taken into consideration. Figures 11a, b, and c compare the flow solutions for three geometries investigated in this study. While the first two designs improved the flow stratifications in the horizontal duct, the third configuration, with the guide vanes inside the first elbow, significantly eliminated the stratification in the horizontal run just before the second elbow inlet. The guided vanes installed inside the elbow also resulted in the minimum pressure drop among the studied geometries. Figure 12 illustrates the 3D velocity contours for the modified geometry with guided vanes inside the first elbow. Although this geometry was not able to create a uniformly distributed flow pattern at the CEM location, it minimizes the flow stratifications caused by the first elbow.

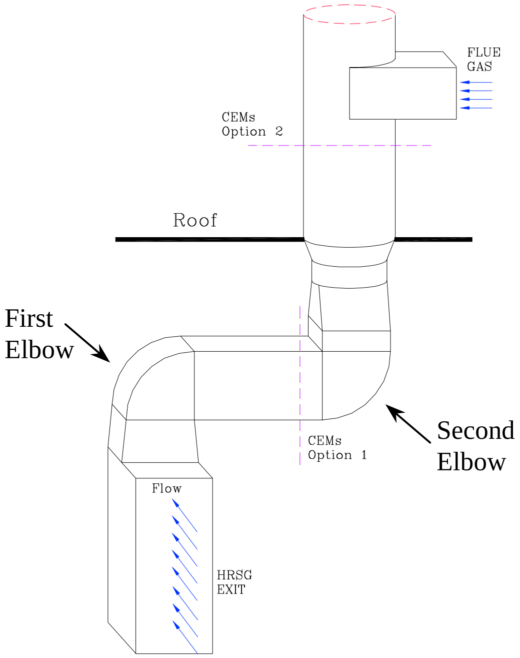

FIGURE 9 – FLUE GAS STACK LAYOUT WITH MOIDIFICATIONS

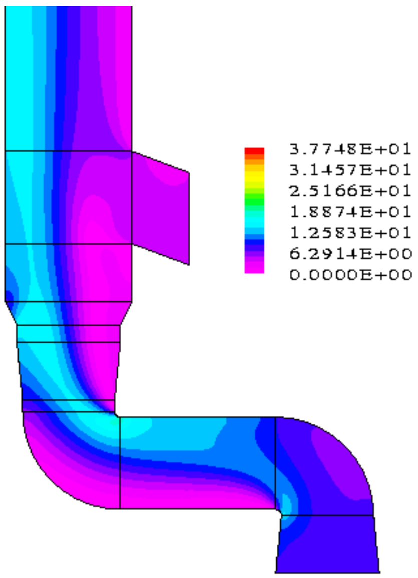

FIGURE 10 – CFD SOLUTION FOR VELOCITY FIELD FOR ORIGINAL DESIGN

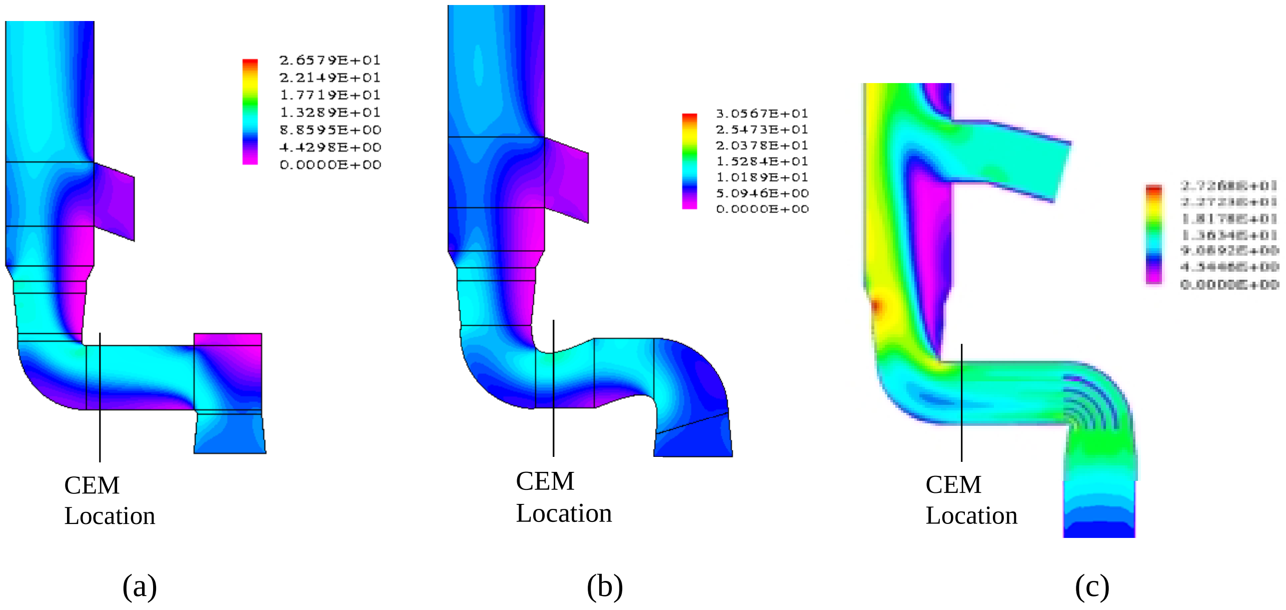

FIGURE 11 – CFD SOLUTION FOR VELOCITY FIELD FOR MODIFIED DESIGNS

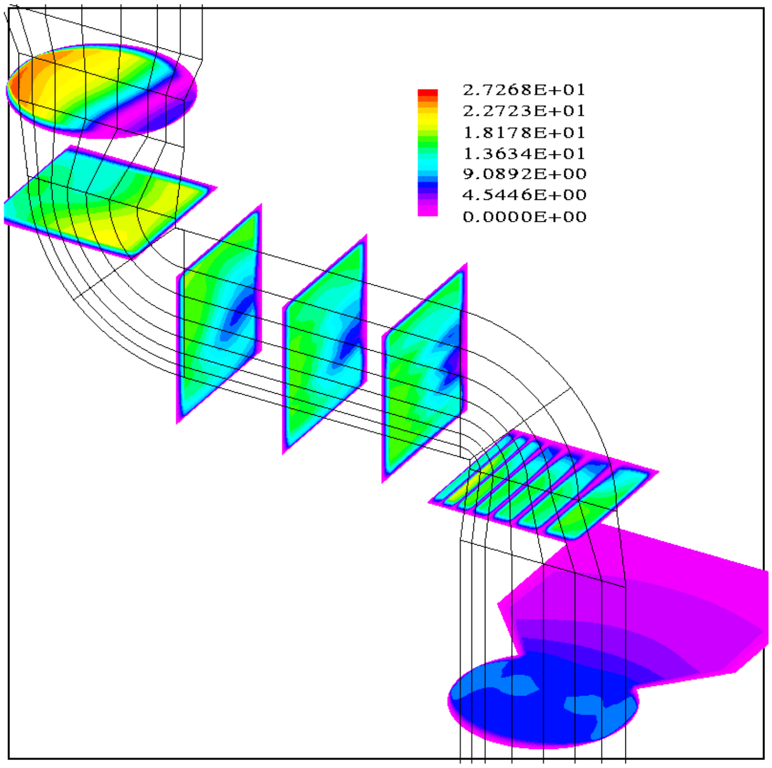

FIGURE 12 - 3D VELOCITY CONTOUR FOR MODIFIED GEOMETRY WITH GUIDE VANES INSTALLED INSIDE THE FIRST ELBOW

CONCLUSIONS

This paper summarizes the issues involved in stack flow measurement and flue gas sampling, using dilution probe systems, for fossil-fired plants CEMs in terms of measurement accuracy. The importance of the use of CFD to do design modifications and determine the CEM measurement locations was illustrated. Studies summarized in the paper have shown positive measurement bias errors which can be as high as 20 percent in some cases. Over-reporting represents the potential for financial losses associated with NO_x and SO_2 emissions trading system in the U.S. The following are recommendations for reducing the CEM flow bias error:

- Carefully plan RATA test and analyze tradeoffs between various test and instrumentation options.
- Select appropriate velocity probe(s) (3-D or S-Type) for stack traverses.
- Use velocity probe calibrated over the flow velocity range of interest.
- Improve instrumentation for velocity head measurement and automate flow calculation procedure.
- Perform stack traverses using the optimal number of traverse points.
- Calculate the magnitude of wall effect or use standard wall corrections as allowed by EPA.

For the dilution probe system a series of modifications have been designed by the authors to improve measurement accuracy of CEMs systems using these type of probe. These modifications have been incorporated in a technology referred to as **DRCalc™**. The **DRCalc™** system provides equipment and software for reducing the probe measurement bias error, and offers the following advantages:

- It corrects for the effects of sample gas temperature and absolute pressure on probe measurement accuracy.
- It corrects for the effect of gas composition (molecular weight) on probe measurement accuracy. It also accounts for the effect of gas composition for the different modes of operation of the probe.
- The improved measurements accurately account for the effect of probe operating temperature and fluctuations in dilution air pressure on dilution air flow rate.
- The improved measurements offer improvements for calibration practices.
- The approach is applicable to any heated and unheated dilution probe system.

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