Alternate Method to Measure Feed Water Flow in Fossil Power Plants

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1 Introduction

Fossil Power Plants require the ability to determine feedwater flow accurately in order to calculate the plant heat rate. Many plants have existing flow nozzles, venturis, or other differential pressure measurement devices to determine this flow rate. Deposits or other degradation on these flow devices changes their discharge coefficient which results in an inaccurate flow measurement thus prohibiting calculation of accurate heat rates. Historically ultrasonic transit time meters have been used to measure flows in power plants. However, they have limitations. The transit time technology injects an ultrasonic signal diagonally through the fluid and then measures the difference in the time that it takes for the ultrasonic pulse to travel upstream versus downstream. It is very sensitive to temperature, transducer installation discrepancies, and pipe geometry conditions. Clamp on Transit time meters rely on assumed flow velocity profile distributions and are susceptible to swirl velocities causing significant errors in the flow measurement.

This paper presents a different ultrasonic measurement approach. This alternate approach measures the velocity of the fluid by determining the time that it takes for the eddy patterns in the turbulent flow fluid to pass a distance between two ultrasonic beams. An ultrasonic beam is injected perpendicular to the axis of the pipe, rather than diagonally as is required for the transit time meter, providing very predictable, robust and stable ultrasonic path. With the CROSS-CORRELATION method the flow velocity profile is imprinted on the eddy patterns which are measured by the meter thus providing information regarding the velocity distribution and accurate flow rate measurement.

Accurate ultrasonic in situ flow measurement of 1% or better is now available to the generation industry using this new method, providing flow information to plant personnel to dial in performance indices like heat rate.

This CROSS-CORRELATION method of flow measurement has been implemented at various fossil stations to provide calibration factors for in plant flow instrumentation.

This paper will address the following areas:

- Underlying physics of Cross-Correlation flow meter
- Description of hardware and software including installation process
- Application issues (sensitivity to various parameters)
- Demonstration of meter accuracy
- Description of meter uncertainty
- Application example

2 Underlying Physics of Cross-Correlation Flow Meters

Turbulent flow structure

Single phase turbulent flow in a pipe can be considered as random assembly of changing structures, formed by the turbulent velocity field, and called Turbulent Eddies. Motion of such eddies along the pipe constitutes the motion of the liquid as a whole and defines volumetric or mass flow rate.

Typical structure of turbulent flow with clearly identified eddies is shown in Figure 1. In many engineering applications, real structure of the turbulence is approximated by a time-average model, as is illustrated in Figure 1.

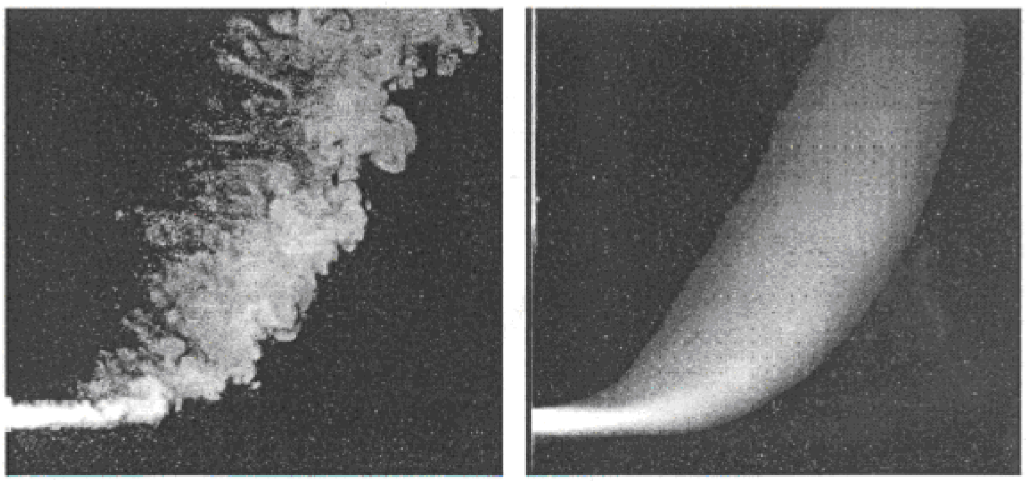

Figure 1. Typical Structure of a turbulent flow and its time-average approximation. (Reference 1)

Principle of Operation

The simplest design of a Cross-Correlation Ultrasonic Flow Meter (UFM) consist of two ultrasonic beams transmitted through a pipe at a certain distance apart along the pipe length, as is shown in Figure 2. Each beam is affected (modulated) by the moving eddies, and after de-modulation generates a time signal.

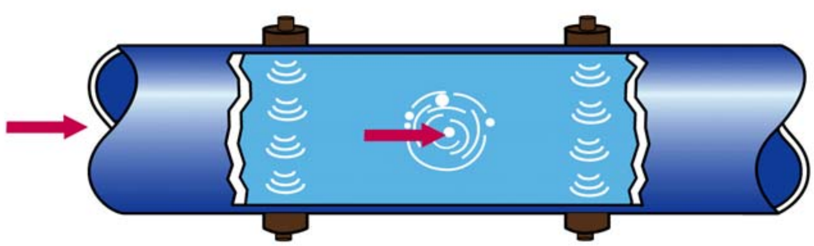

Figure 2. Cross-Correlation Flow Meter Principle of Operation

For any specified time interval T, the time signal is completely defined by the set of eddies, which were affecting the beam during this time interval. The set of eddies is unique and not repeatable because it is a subset of a random assembly. A second beam, which is positioned on the pipe a distance L downstream of the first one, is affected by the same assembly of eddies with a certain time delay τ^*. Eddies in the selected set do not form exactly the same pattern when they move along the pipe; therefore, the signal generated by the second beam is not exactly identical to the first one. However, there is a measurable correlation between the two. Delay time between signals, τ^* can be determined by a mathematical process which compares of two signals.

Assuming that X(t) and Y(t) are two signals generated by the interaction of the eddies with upstream and downstream ultrasonic beams respectively, and introducing signal $Y(t+\tau)$ which is equal to signal Y(t), but is shifted in time by time-shift τ. To obtain quantitative estimation of the similarity between X(t) and $Y(t+\tau)$ within time interval T, an average of the difference between two signals, $\Delta(\tau)$ can be calculated as follows:

Equation 1:

$$\Delta(\tau) = \frac{1}{T}\int_0^T [X(t) - Y(t+\tau)]^2\, dt$$

The maximum similarity between signals is achieved at point $\tau = \tau^*$ where $\Delta(\tau)$ is minimum. From Equation 1 it follows that the minimum of $\Delta(\tau)$ corresponds to maximum of function $R(\tau)$, which is defined by the following equation:

Equation 2:

$$R(\tau) = \int_0^T X(t) \cdot Y(t+\tau) dt$$

Function $R(\tau)$ is called the Cross-Correlation Function. Time delay τ^* between two time signals is calculated as a position of the maximum of a Cross-Correlation Function $R(\tau)$. Transport velocity of the set of eddies (measured velocity Vm) is calculated as follows:

Equation 3:

$$V_m = \frac{L}{\tau}$$

Where: L - Distance between two ultrasonic beams.

In general case, measured velocity Vm is not equal to the cross-section average flow velocity Va. The relation between Vm and Va depends on liquid properties (Reynolds Number) on hydraulic characteristics of the flow (piping geometry and meter location) on meter design (number of ultrasonic beams and their orientation) and on signal processing algorithm (signal frequency band, filters characteristics). The ratio of the bulk flow velocity Va to the measured flow velocity Vm is defined as Hydraulic Factor C. Similarly as with other flow measurement instruments, the value of C has to be obtained based on laboratory calibration or other analysis. If C is known the flow rate in a pipe F is calculated by the following Equation:

Equation 4:

$$F = \rho \cdot A \cdot C \cdot \frac{L}{\tau^*}$$

Where:

ρ - Fluid density

A - Pipe cross-section area

Theory of flow measurements, using cross-correlation technique, was developed in the 1960’s and is presented with greater detail in Reference 2.

Comparison with Conventional Transit Time Meters

The basic difference between the cross-correlation and transit time technologies is the way that each of these meters measures the velocity of the fluid within the pipe. The transit time technology injects an ultrasonic signal diagonally through the fluid and then measures the difference in the time that it takes for the ultrasonic pulse to travel upstream versus downstream. It can then be shown that the difference in these times is approximately proportional to the velocity of the fluid in the pipe. In this approach the ultrasonic path changes direction on each interface between transducers, pipe wall and liquid inside the pipe. Therefore, it is very sensitive to temperature change and to transducer installation discrepancies due to alignment and pipe conditions. Measured time difference, which is on the order of a few microseconds, has to be measured with accuracy of few nanoseconds.

The cross-correlation meter measures velocity of the fluid by determining the time that it takes for the fluid to pass distance between two ultrasonic beams. An ultrasonic beam is injected perpendicular to the axis of the pipe, rather than diagonally as is required for the transit time meter, providing very robust and stable ultrasonic path, which is not effected by the temperature change and is not sensitive to transducer alignment. For typical industrial applications the magnitude of the delay time is in order of 30 – 100 milliseconds, which can be measured very accurately.

A significant difference between the time of flight meter and the cross correlation meter is the precision required for measurement of the time difference (see Figure 3).

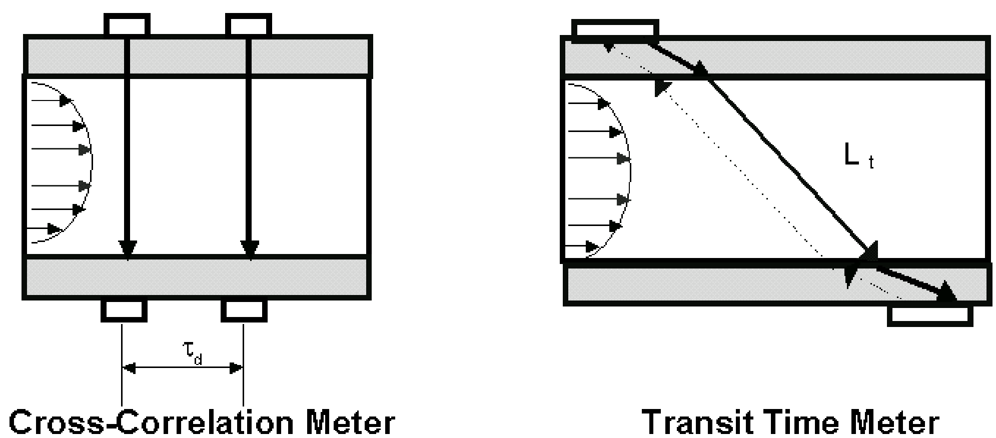

Figure 3: Comparison of Cross-Correlation vs. Transit Time technologies

Another significant feature of the cross-correlation technology is that the bulk flow velocity is not derived from measurements of local characteristics of the velocity profile. The cross-correlation meter measures directly the volumetric flow rate by measuring the time that is required for a known volume to travel through the pipe cross-section. The movement of that volume is determined by tracking the movement of turbulent eddies contained in the volume. Therefore, the meter is not directly affected by radial or angular velocity components in the flow. Effective sampling area of the flow is defined by the size of eddies, but not by the diameter of the ultrasonic beam, as it is in transit time meters.

3 Hardware-Software Components and Installation Process

The cross-correlation UFM consist of the following components: (a) a transducer, which is mounted on the pipe and supports two transmitter- receiver pairs of ultrasonic probes; (b) a Signal Conditioning Unit (SCU), which generates transmitter signals to drive piezoelectric crystals and provides demodulation of the carrier ultrasonic signal, (c) a multiplexer which allows monitoring of up to eight transducers and (d) a computer, which provides interface between analog and digital components of the signal processing, analog signal processing, and user interface. Hardware components of the meter are shown in Figure 4.

Figure 4. CROSSFLOW Hardware Components

Software package of the meter provides user interface and supports the following functions:

- Hardware configuration, such as selection of electronic filters frequency band and ultrasonic frequency band
- Optimization of signal processing parameters, such as sampling rate, data acquisition time, signal rejection/acceptance criteria
- Input of pipe and flow parameters, which are required for flow rate calculation, such as pipe internal diameter, distance between ultrasonic beams, pipe and transducer thermal expansion coefficients, etc.
- Presentation of historical flow trend

- Diagnostics of the system performance and other trouble-shooting tools
- Data storage

Installation of the system does not require flow interruption and can be performed on a hot or cold pipe. Time of installation significantly depends on required accuracy, and may vary from 15 minutes to a few hours. Typical installation time for one transducer is 2 – 4 hours. Normal installation process consists of the following steps:

- Assessment of the piping configuration for selection of the location for transducer installation. The location should be accessible, and upstream piping geometry should not include features that may produce unpredictable effect on flow. For example, effect of a partially closed valve on downstream meter might be difficult to predict if valve position is not known or is not stable.
- Arrangement of the work-space, such as construction of platform, radiation protection etc.
- Preparation of pipe surface and pipe measurement. Accurate measurement of the pipe diameter and pipe wall thickness is required to provide accurate input for calculation of the pipe cross-section area; depending on condition of installation, pipe measurement may take few hours. Pipe surface has to be cleaned using sandpaper
- Installation of the transducers
- System tuning and commissioning. This stage includes optimization of the ultrasonic transmission, testing of the electronics components, preliminary data collection and optimization of signal processing parameters.

4 System Validation and Verification in Laboratory and Field Environment

Cross-correlation UFM had been used for various applications in nuclear industry for more than 30 years in Canada, USA, and other countries. Today more than 100 installations are operating world wide.

The first experimental study of the Velocity Profile Correction Factor (VPCF) using the cross-correlation clamp-on ultrasonic flow meter for single-phase flows was conducted in Ontario Hydro between 1985 and 1990. This high temperature test was designed specifically applications in CANDU reactors. Pipe dimension (14 inch and 16 inch diameters), flow pressure, flow temperature and flow velocities were similar to the typical feedwater system in CANDU reactors.

In 1994 - 1996, a study of a cross-correlation ultrasonic flow measurement technology for single-phase flow was conducted by AMAG. The underling physical phenomena were analyzed, and an equation was obtained which described the dependence of the VPCF on Reynolds Number (Reference 3 & 4).

Since 1994 the meter was evaluated in a number of laboratory tests in the following laboratories: Alden Flow Laboratory; National Institute of Standards and Technology in USA; Hydraulic Center of National Research Council (Canada); Chatou Flow Laboratory in Electricity de France, in MHI Takasago Flow Laboratory and others. Results of some of these tests are shown in the figures and tables section and discussed below.

The system is currently being used to measure various cooling system flows in power plants in the US and Canada.

Table 1 presents summary of the tests conducted in Chatou Flow Laboratory in France on 14” carbon steel pipe at four different Reynolds Numbers. The UFM measurements were obtained in a blind test, where UFM flow readings were submitted to the Laboratory personnel before laboratory reference flow readings were available to UFM operator. In this test, the reference instrumentation was orifice plate with 95% confidence interval uncertainty 0.3%. See Table 1.

Test #	Date	Reynolds Number	CROSSFLOW	CHATOU	DIFF(%)
1	9-Sep	$1.3*10^6$	1082.73	1084.54	0.17%
2	9-Sep	$1.1*10^6$	901.19	902.7	0.17%
3	9-Sep	$0.86*10^6$	701.21	699.73	-0.21%
4	10-Sep	$0.73*10^6$	589.43	590.53	0.19%

Table 1: Chatou Test Data

A similar blind test was conducted at NIST, where different clamp-on UFMs from five vendors were compared with the NIST weigh tank reference reading. The test was conducted at three different Reynolds Numbers: 400,000, 1,600,000, and 2,900,000. Summary of the results is shown in Figure 5, which was taken from the NIST Report, Reference 5. In this figure the Cross-Correlation Meter data is displayed over “E”.

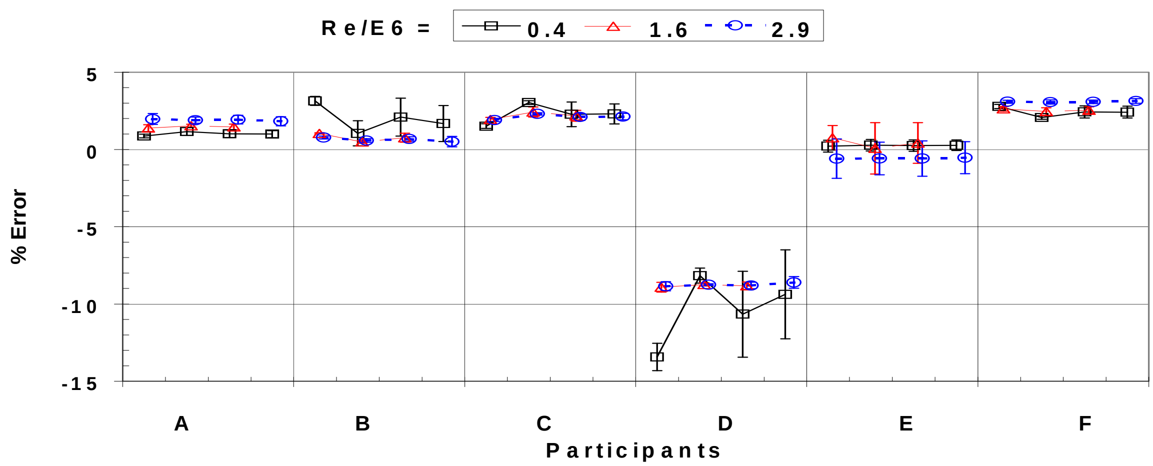

Figure 5: NIST Blind Test

Flow Change response testing was performed comparing the CROSSFLOW meter to a magnetic meter and an 8 path chordal meter. The results of this test are shown in Figure 6.

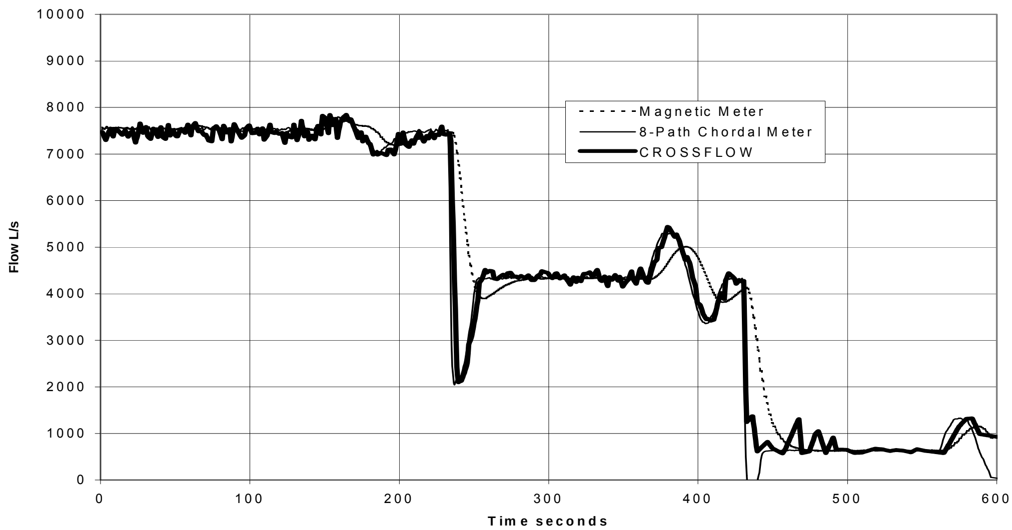

Figure 6: Flow Change Response Testing

5 Meter Sensitivity

Detailed analysis of different factors, which may affect meter performance and its reading, was conducted by the cross correlation meter vendor. This study, consisting of a complete system, which combines the meter, the pipe and the flow, was considered based on non-dimensional system analysis and on physical phenomena associated with acoustics, hydraulics and signal processing. Based on this analysis and on operation experience, the following critical parameters were identified:

Reynolds Number

$$\mathrm{Re} = \frac{\rho \cdot D \cdot Va}{\mu}$$

Reynolds number represents normalized viscosity of the fluid. It affects hydraulic parameters of the flow and, as a consequence of that, affects Hydraulic Factor C.

Most significantly the Hydraulic Factor C is affected by Reynolds Number in a long straight pipe. Dependence of C on Re for such case is described by theoretical equation, which was validated in numerous laboratory tests in broad range of Re. (See previous section). This equation shows weak dependence of C on Re. For example, when Re changes from 1 million to 10 million the change of C is about 1%. In the system software the Re is calculated by iterations based on measured velocity Vm and on equation for C. In all practical situations, the error in Re calculations results in a negligible error in C. In total uncertainty balance the uncertainty on C as a function of Re is estimated conservatively as 0.25%.

Equivalent Hydraulic Roughness

Hydraulic roughness, similarly to Reynolds Number, affects turbulent and averaged flow characteristics. The Moody Diagram defines dependence of pipe friction factor on Equivalent Hydraulic Roughness. The Theoretical equation for C and Moody Diagram can be used to calculate C if Equivalent Hydraulic Roughness is known. If hydraulic roughness is not known and can be estimated approximately within a certain range, the corresponding uncertainty of C can be calculated, and should be included in total uncertainty. An order of magnitude of the possible roughness effect on hydraulic factor can be seen from the following example: For 12” pipe, made of a typical construction steel, with flow rate of approximately 300 l/s (approximately 5000 GPM) at room temperature, C = 0.925, which is 0.4% different from its value for smooth pipe, C=0.929.

Position of the transducer on the pipe

The Position of the transducer on the pipe with respect to the upstream piping geometry, normalized to pipe diameter, together with Reynolds Number and Hydraulic Roughness, defines velocity distribution in the pipe at the location of the transducer.

If the pipe run upstream of the location of the transducer is not long enough, the standard equation for the Hydraulic Factor C is not applicable. In this case, the value for C should be determined in calibration test. Most typical piping geometry is a combination of elbows. Therefore a single 90-degree elbow was selected as benchmark geometry (BM), which is used to compare dependence of C on the distance from flow disturbance for other piping configurations. The following example illustrates this approach:

Figure 7 shows real piping where the meter was installed downstream of a combination of elbows. To determine Hydraulic Factor C for such piping geometry, two laboratory models were manufactured, a Test Model (shown in Figure 8), and a Benchmark Model. A set of UFM transducers was installed on a straight run test section downstream of the pipe elbows. Transformation of the test loop from Test Model to the benchmark geometry was conducted such that the test section with all transducers remained unaffected, and only the upstream section of the loop was replaced. This approach provides accurate comparison of the test section and benchmark geometry by eliminating uncertainty associated with test section pipe area and with transducer installation. Factor C was determined by comparing UFM readings with weigh-tank data. Results of the test are shown in Figure 9. It can be seen that the difference between the Test Model and the benchmark is within 0.5% for the locations between 8 to18 pipe diameters from the nearest upstream elbow.

In general, numerous laboratory tests with different piping geometries have shown that on a distance of 8 pipe diameters and longer, deviation of Hydraulic Factor C from its Benchmark distribution is +/- 1% for a broad range of flow disturbances.

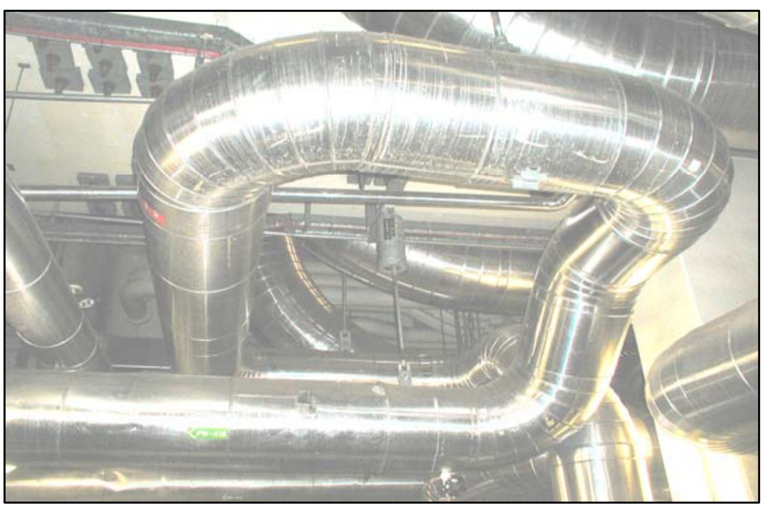

Figure 7. Piping Geometry with Combination of Elbows Upstream of the Location of the UFM Transducer

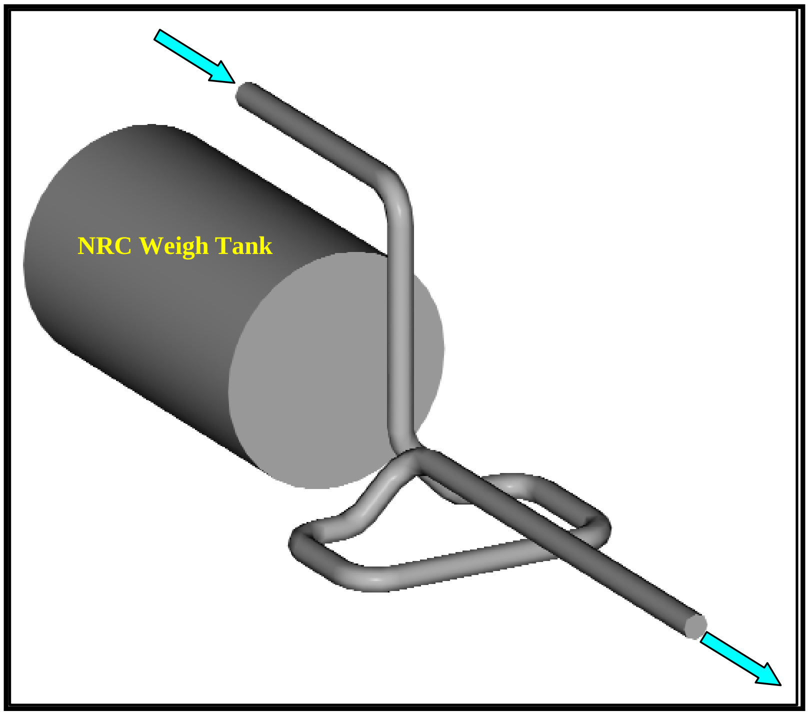

Figure 8. Test Model of the Piping Configuration, shown in Figure 7

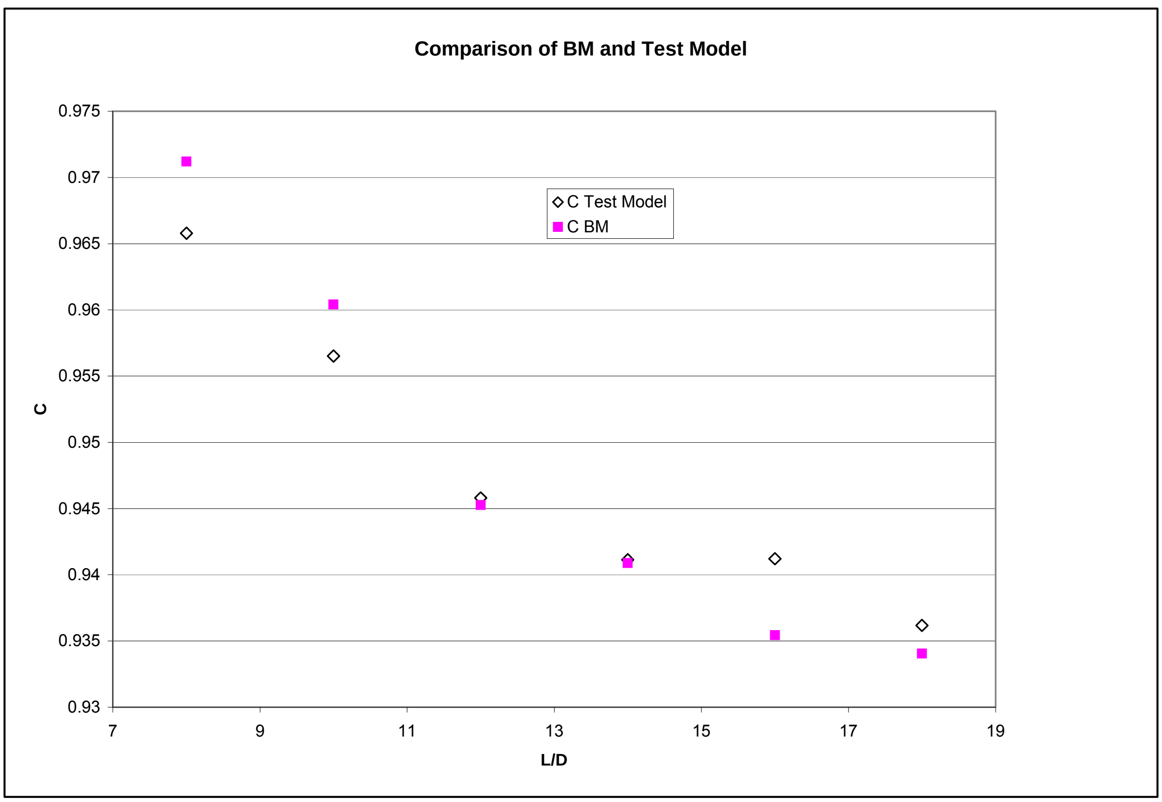

Figure 9. Comparison of Test Model and BM Piping Configurations

Flow Frequency

Flow Frequency is defined as a ratio of flow velocity to pipe diameter, F= Va/D - represents scaling factor for turbulence spectrum in the pipe, and is associated with the size of turbulent eddies.

Demodulated signals, generated by interaction of moving eddies with the ultrasonic beam, are processed using filters with a certain set of frequency bands. Selection of the frequency band of the filters defines a window of eddies' sizes, as they are detected by the meter, and may result in different measured velocities. Appropriate adjustment of the filters eliminates this effect. This is discussed in more detail in Reference 3.

Pipe Temperature

Pipe temperature may affect flow density, flow viscosity, and acoustical characteristics of the system. Pipe temperature is used as an input for flow rate calculation to account for flow density, for pipe thermal expansion, and for flow viscosity. Possible error associated with last two factors is negligible for typical uncertainties in temperature input. The most significant affect of temperature is associated with flow density; 10 C uncertainty in flow temperature results in approximately 0.1% uncertainty in flow density.

Change in speed of sound due to temperature change is another factor, which may potentially affect ultrasonic transmission through the pipe wall and the fluid. In cross-correlation meters this effect can be eliminated by optimization of the range of ultrasonic frequencies depending on specific application. For reactor coolant flow measurements, this allows continuous flow monitoring in temperature range from 20°C to 320°C.

Acoustical noise

Acoustical noise occurs in pipe flow as a result of interaction of acoustical waves. Presence of such noise may displace the position of the maximum of the cross-correlation curve, resulting in flow reading bias. In the last three years, various methods of on-line and off-line signal analysis have been developed, which allow identification of the presence of the acoustical noise and determination of its effect on time delay calculation.

6 Uncertainty Analysis

Overall Uncertainty

The flow as measured by the cross correlation UFM is calculated based on the following equation:

Equation 5:

$$W = C_f \frac{\rho A L}{\tau}$$

Where:

Cf : Flow Bulk Correction Factor
ρ: Flow Density
A: Pipe cross-sectional area
L: Transducer Spacing
τ: Time Delay

The uncertainty associated with this equation can be expressed as:

Equation 6:

$$\varepsilon_w = \left[\varepsilon_{c_f}{}^2 + \varepsilon_\rho{}^2 + \varepsilon_A{}^2 + \varepsilon_L{}^2 + \varepsilon_\tau{}^2\right]^{0.5}$$

All of the above parameters are loop dependant and are based on measurements taken in the plant during the test. The time delay is comprised of the instrument accuracy of 0.035ms along with flow measurement and statistical scatter.

Flow Bulk Correction Factor (Cf)

Equation 7: $$C_f = C_p \cdot C_o \cdot \left[1 + \Delta C\right]$$

Where:

C_f =	Flow Bulk Correction factor for flow at a point L/D downstream of a flow disturbance
C_p=	Piping configuration factor for upstream disturbances (excludes elbow bends)
C_o=	Flow hydraulic correction factor at a specific Reynolds number
ΔC=	Change in hydraulic correction factor due to upstream elbow bend

The uncertainty associated with the Co is dependant on the actual pipe configuration upstream of the meter location. Based on the lab analysis compared with in plant testing the prediction for this correction factor is within 0.25% however, for the typical installation discussed in section 7, 0.5% is assumed.

In addition, uncertainty relative to piping configuration and Reynolds number are taken into account. With regard to the Reynolds number the random uncertainty of the inputs to the calculation are also considered. The confidence interval for Reynolds number is determined by taking the derivative of the Reynolds number with respect to velocity, density and dynamic viscosity.

Flow Density (ρ)

The uncertainty of density is determined by the uncertainty of the pressure and temperature measurement of the fluid. The confidence interval for the density is determined by taking the derivative of the density with respect to temperature and pressure.

Pipe Cross-sectional area (A)

The uncertainty of the pipe cross-sectional area is determined by evaluating data taken during installation such as pipe wall thickness, pipe temperature and pipe outside diameter measurements. Uncertainty for thermal expansion effects is also considered. The elements of the internal diameter measurements are as follows:

Equation 8: $$d_{i@\,y[x°,x°+180]} = d_{o@\,y[x°,x°+180]} - t_{y[x°]adj} - t_{y[x°+180]adj}$$

Where:

di@y[x°, x°+180] =	Inner diameter at location y and position x +180
do@y[x°, x°+180] =	Outer diameter at location y and position x +180
ty[x°]adj=	(SVsample/SVcalref)* ty[x°]+Xcalref
ty[x°+180°]adj=	(SVsample/SVcalref)* ty[x°+180°]+Xcalref
ty[x°] =	Measured wall thickness at location y and position x
ty[x°+180°] =	Measured wall thickness at location y and position x+180°
SVsample=	Sound velocity of pipe material sample
SVcalref=	Sound velocity of calibration block
Xcalref=	Bias correction in wall thickness measurements due to calibration block material property differences
y =	Location along the pipe
x=	Radial location around the pipe— 0°, 45°, 90°, or 135°

Transducer Spacing

The uncertainty of the transducer spacing is determined by evaluating measurement data taken during installation. Uncertainty for thermal expansion effects is also considered.

To determine transducer spacing, measurements are taken on the CROSSFLOW bracket prior to its installation on a pipe or at the time of installation The bracket consists of a male half and a female half that are fastened together when the unit is mounted to a pipe.
Measurements are taken to find the outer diameter separation of the two mounting holes on both male and female sides. Then each mounting hole inner diameter on both sides is measured. There are 6 measurements and the process is completed 3 times. The average of each measurement is found and then an average center-to-center spacing can be found as in equation 9.

Equation 9:

$$L_{spacingmeas} = \frac{L_{ms} - L_{mh} + L_{fs} - L_{fh}}{2}$$

Where:

Lms= average OD separation on male side
Lmh= average hole ID on male side
Lfs = average OD separation on female side
Lfh = average hole ID on female side

Time Delay

The time delay data is collected by the CROSSFLOW meter and is used in Equation 5 to calculate the flow inside the pipe. The time delay average (tdelay), standard deviation (σtdelay), and statistical uncertainty (εtdelay) are determined for the collected time delay. In addition to the statistical uncertainty, the total 95% confidence interval for the time delay must also include instrumentation uncertainty and a noise correction uncertainty. The total time delay uncertainty (εtxflow) is found by taking the square root sum of the squares of these uncertainties.

Equation 10:

$$\varepsilon_{tflowx} = \left[\varepsilon_{tdelay}^2 + \varepsilon_{CN}^2 + \varepsilon_{tinstr}^2\right]^{0.5}$$

Where:

εtdelay= Statistical uncertainty of time delay data
εtinstr =   Uncertainty of CROSSLFOW instrumentation
εCN   =   Uncertainty noise correction factor

Acquired time delay data and the instrumentation uncertainty depend on certain software and hardware parameters. The optimum configuration of these parameters is determined at the time of installation and tuning. The Cross Correlation flow meter utilizes multiple samples of the time delay measurement to achieve a relatively low uncertainty due to random error. This is based on the central limit theorem, which basically states that as the sample size (N) becomes large, the following occur:

1. The sampling distribution of the mean becomes approximately normal regardless of the distribution of the original variable.
2. The sampling distribution of the mean is centered at the population mean of the original variable. In addition, the standard deviation of the sampling distribution of the mean approaches the standard deviation divided by the square root of the sample size.

The variability in a measurement system is driven by the standard deviation of the measurements taken. By taking multiple samples of the same measurement, the standard deviation of the sample means is reduced by a factor of one divided by the square root of the sample size.

Uncertainty Example

Flow through a pipe needs to be held to +/- 2 ft/sec (total tolerance = 4 ft/sec)
Allowable measurement system variation = 1%= .04 ft per sec

30 measurements are taken.
Standard Deviation (s) of these samples =0.1 ft/sec
Expected Measurement System Error = 4 * s = 0.4 ft per sec

Take 30 measurements, but each measurement is an average of 100 samples.

Standard deviation (s) of these samples = $0.1/\sqrt{100}$) = 0.01 ft/sec

Expected measurement system variation = 4 * 0.01 = .04

Table 2 provides typical uncertainty values for the various inputs to the flow equation.

Parameter	Uncertainty (%)
Cf	0.63
ρ	0.10
A	0.242
L	0.100
T	0.128
Flow Freq	0.100
Noise	0.456
Total	0.842

Table 2: Typical Uncertainty Values

7 Application Example

Background

Huntington coal fired power plant currently measures final feedwater flow on two units with flow nozzles. The accuracy of these nozzles is unknown and there were indications of errors in the calculation of the turbine cycle heatrate. The facility sought to demonstrate the uncertainty levels available with the CROSSFLOW Ultrasonic Flow Meter and to provide correction factors for the nozzle flow readings. Huntington station expected the nozzles were indicating feedwater flow 3-5 % higher than actual. The reheater spray flows were also measured with the CROSSFLOW meter however they are not discussed in this paper.

Test Setup

Piping Configuration

The piping configurations considered by this report are the final feedwater lines leading to the economizer. Both units have similar final feedwater piping configurations. A diagram of the Unit 1 final feedwater piping configuration can be seen in Figure 10. The Unit 2 final feedwater piping is similar in configuration to Unit 1.

As seen in Figure 10 the final feedwater flow measurements are taken on 20 inch pipe and the nearest upstream flow disturbances are the 90° bends. The flow at both locations is expected to be fully developed allowing sufficiently accurate measurements to be taken. Figure 11 is a section of the PID indicating the existing flow nozzle and piping configuration. Figure 12 shows the location of the flow meter relative to upstream conditions.

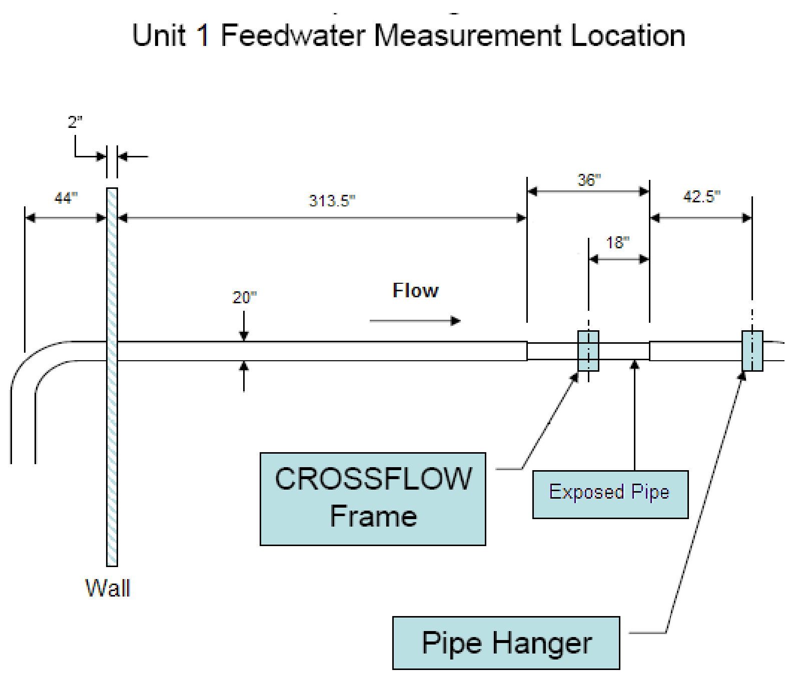

Figure 10: Feedwater Measurement Location Sketch

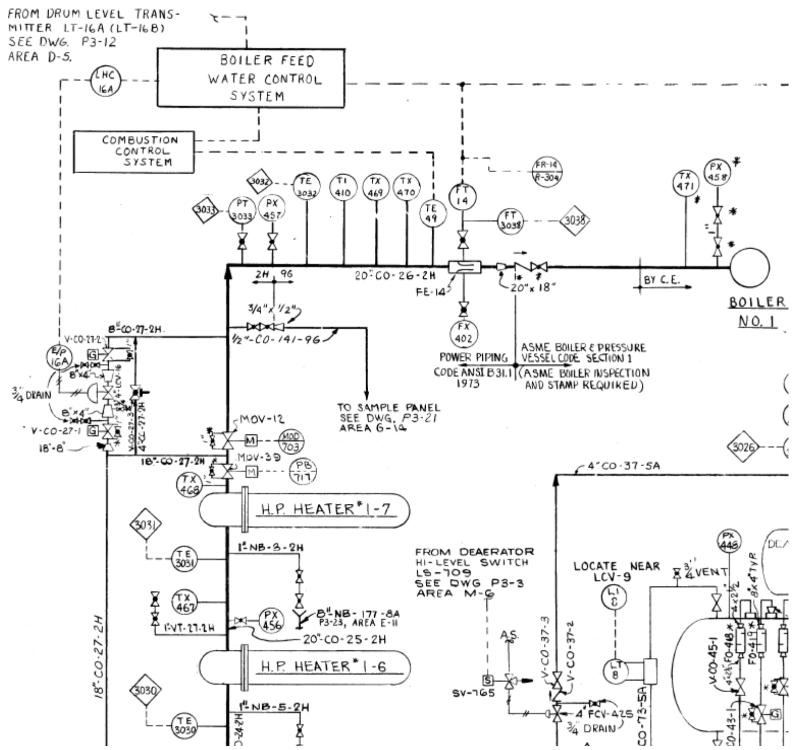

Figure 11: Feedwater PID

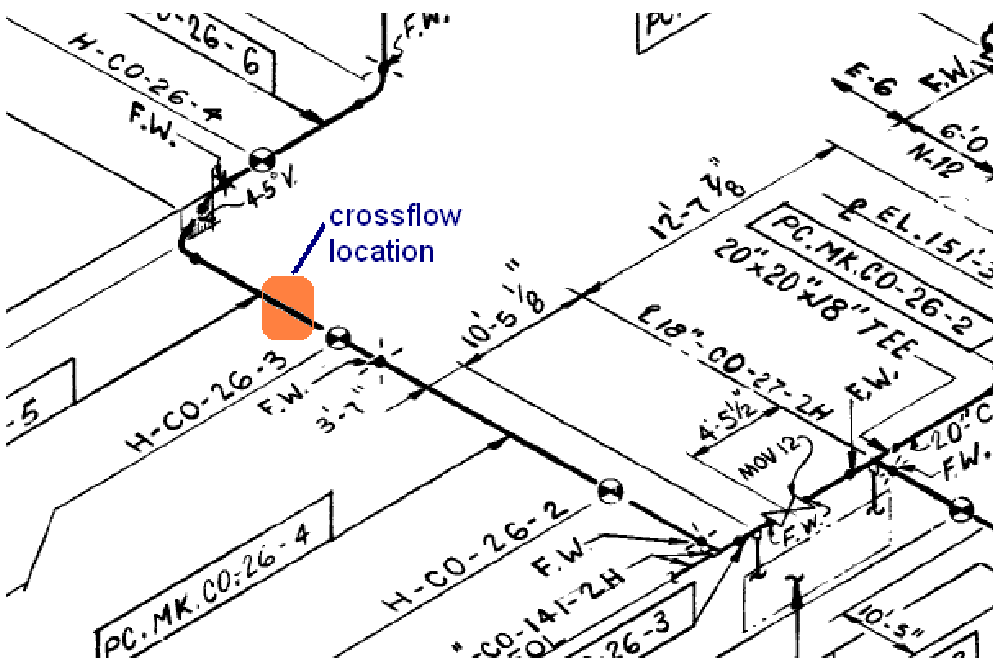

Figure 12: Feedwater Isometric

Measurements

Pipe Outer Diameter, Pipe Temperature Pipe Wall Thickness Bracket Outer Diameter Separation, Bracket Hole Inner Diameter Measurements, and Bracket temperature measurement were all taken to precisely determine the inner diameter of the feedwater pipe, including corrections for temperature. Multiple readings were taken to establish a statistical uncertainty for the inner pipe diameter.

Data Gathering

The Unit 1 feedwater data was gathered for approximately 21 hours and 919 good time delays were measured. Unit 2 feedwater measurements were gathered for approximately 9 hours and 803 good time delays were measured.
Simultaneous plant measurements for feedwater flow, pressure, temperature on both units were provided for the same time periods above.

Feedwater Pressure Adjustment

The pressure measurements used for the CROSSFLOW meters in this report were taken downstream of both meters. The elevation increases by 65ft 2in between the CROSSFLOW meters and the pressure point PT3033. A pressure adjustment due to this elevation change is accounted for. However, this calculation assumes that pressure drops due to friction and other geometry losses are negligible.

The pressure correction due to the elevation change is calculated below.

Equation 11:

$$\Delta P_z\,(psi) = \Delta z \cdot \rho \cdot g \cdot \frac{ft^2}{144 in^2} \cdot \frac{lb_f}{32.2 lb_m \cdot \frac{ft}{s^2}}$$

Where:

Δz = 65.167 ft
G = 32.2 ft/s2
ρ = 51.083 lbm/ft3 *
ΔPz = +23.12 psi

*Average temperatures and pressures from plant parameters are used to calculate density.

Results and Conclusions

Measured Flows and Uncertainties at Time of Calibration

The results for the measured flows and related uncertainties are shown in Table 3. The Correction factors for the flow nozzles are included in Table 4.

Meter/Flow :	WU1 FW	WU2 FW
Appendix	A	B
CROSSFLOW Flow (lbm/hr)	3300661	3391728
Flow Uncertainty (%)	0.7164	0.6716

Table 3: Test Results

	Unit 1 Feedwater	Unit 2 Feedwater
Appendix	C	C
Correction Factor	0.958	1.035
Correction Factor Uncertainty (%)	0.6263	0.5133

Table 4: Correction Factor

Analysis of Results

Since the correction factors for the plant nozzles showed an unusually large difference, further analysis was performed to compare the results from the CROSSFLOW system with alternate indications of flow through the turbine cycle. The results of this analysis are presented below in Table 5. The CROSSFLOW measurements indicate an approximately 2-3% difference between the Unit 1 and Unit 2 flow through the cycle. Plant data was reviewed to determine if other plant indications showed a similar difference. Since pressures downstream of the turbine inlet are normally linear with respect to throttle flow, a comparison was made between the units to evaluate the throttle flow difference between the units.

The other plant parameters that match the magnitude of the measured flow differences are Generator Load and Extraction Pressures for feedwater heaters 6 and 7and the final feed temperature.

These plant parameters indicate that there was a difference in the operation of Units 1 and 2 during the measurement periods. This difference is matched by a same magnitude difference in feedwater flow as indicated by the CROSSFLOW meter.

The overall correction to the plant heatrate based on these measurements is on the order of 300 Btu/kwhr. Additionally the plant operation is limited by the measured feedwater flow; therefore an accurate flow measurement can result in increasing plant output or validation that the plant is operating within the prescribed limits.

	CROSSFLOW FW Flow lbm/hr	Generator Load MWG	FWH 6 Extr. Press psig	FWH 7 Extr. Press psig	Econ In Feedwater Temp degF
Unit 1	3300666	461	298	585	479
Unit 2	3390895	474	303	602	481
Difference (%)	2.7%	2.6%	1.4%	2.9%	2.1%

Table 5: Comparison of plant Data

8 Conclusion

This paper demonstrates that the use of the cross-correlation flow measurement method is an acceptable alternative for measurement of feedwater flow in coal fired power plants with the ability to achieve acceptable uncertainty. The principals of the flow meter are based on established turbulent theory, the installation practices are thorough and well defined, the accuracy has been well documented and the uncertainty determination is rigorous. The application shown is an example of a flow measurement technique that can solve a problematic flow measurement. The results of this flow application were consistent with the plant performance and allows a more accurate determination of plant heatrate. Additionally the plant has limitations on feedwater flow so an accurate measurement of feedwater flow will allow the plant to safely operate at its maximum generation.

9 References

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