Experience of Application of Clamp-on Cross-Correlation Flow Meter in Nuclear Industry.

[1]Y. Gurevich, [2]V. Ton, [2]S. Kotenyov, [2]C. Zhao, [3]B. Sharp and [3]A. Lopez
[1] Daystar Technology Inc, Ontario, Canada, [2]Ontario Power Generation, Ontario, Canada,
[3]Advanced Measurements and Analysis Group Inc, Ontario, Canada

Abstract

The cross-correlation clamp-on flow meter, CROSSFLOW, developed and manufactured by AMAG, has been used over the world for over 15 years for flow measurements in various systems in nuclear and fossil power plants. Prior that, OPG has used similar technology in Canadian nuclear power plants since 1980-ies. Two recent examples of the application of the clamp-on cross-correlation technology are presented in this paper. In first example OPG meter was used to verify accuracy of ASME nozles installed in condensate flow lines. In second example AMAG meter was used to measure Diesel Cooling Water (DCW)

1. Introduction

The cross-correlation clamp-on meter, CROSSFLOW, developed and manufactured by AMAG, has been used over the world for over 15 years for feedwater flow measurements, reactor coolant flow measurements and for flow measurements in various other systems in nuclear and fossil power plants. Prior that, Ontario Power Generation has used ultrasonic cross-correlation clamp-on flow meters in Canadian nuclear power plants since 1980-ies.

First example of application of the technology describes OPG meter used for condensate flow measurements in Canadian Nuclear Power Plant; second example describes installation of AMAG meter, CROSSFLOW in US nuclear power plant.

In the simplest design of the meter, two ultrasonic beams are transmitted diametrically through the pipe. These beams are separated by a known axial distance. Each beam is affected (modulated) by an ensemble of moving turbulent eddies, and after de-modulation, a signal is generated in the time domain. As the eddies move down the pipe they modulate the carrier frequencies of each of the beams in a similar manner; however the demodulated signals are offset in time. Time delay between the two time signals is obtained as a position of the maximum of the cross-correlation function of the signals. Knowing time delay and distance between ultrasonic beams, velocity of the flow can be determined [1-3].

Flow measurements technology based on the cross-correlation principle has a number of advantages for clamp-on applications. These advantages are:

- Stability of he ultrasonic beams because they are orthogonal to the surface of the pipe and the interfaces between the pipe wall and the liquid and those separating different materials inside ultrasonic transducer. This makes meter very robust to installation process, since it is impervious to pipe surface conditions and temperature variations.

- Sampling area of the flow is determined by the size of turbulence eddies, affecting ultrasonic beam, but not by the size of the beam itself. This makes the meter less sensitive to the flow velocity distribution at the meter location on the pipe.
- The time delay measured by the meter is determined by the flow velocity and by the distance between two pairs of ultrasonic beams, but not by the velocity of the sound. The measured time delay is in order of the pipe diameter divided by the flow velocity, or milliseconds. This makes the meter electronic circuits less sensitive to environmental conditions.

The clamp-on design not only offers an advantage of being totally non-intrusive but, more importantly provides practical means of verifying accuracy of the flow measurement by installing more than one transducer on the same flow path. Two recent examples of the application of the clamp-on cross-correlation technology are presented in this paper.

The first example deals with the measurements conducted by OPG using OPG meter on the main condensate lines in a nuclear power plant with a flow rate of about 1000 l/s and temperature of 130^0C. The plant has four identical units, and the condensate line in each unit is equipped with an ASME nozzle. Therefore, there are four ASME nozzles in total installed in four flow lines with identical piping configuration and with approximately equal flow conditions, not achievable in laboratory tests.

Since one of the nozzles had undergone a thorough inspection, it was decided to compare the nozzle calibration by obtaining independent flow measurement on each flow line using identical installation of a clamp-on cross-correlation meter, instead of removing the nozzles and sending them for re-calibration,

The measurements had provided a unique opportunity to compare two different technologies on four identical industrial installations under plant operating flow conditions, which cannot be reproduced in any existing flow facilities with sufficiently accurate reference instrumentation.

The second example deals with flow measurement in Diesel Cooling Water (DCW) supply line in a nuclear power plant. The existing flow measurement instrument did not provide reliable flow measurements, and the AMAG's CROSSFLOW meter was used to insure that the flow assumed in the design basis is supplied to the system. This example illustrates the use of multiple installations of the clam-on meter to measure a flow in a pipe over a wide range of flow regimes.

Outline of the projects and results of the measurements are presented and discussed bellow.

Results presented in the paper became possible due to the efforts of many colleagues from OPG, AMAG and from nuclear utilities in Canada and in USA. Very valuable comments and suggestions were obtained from Dr. D. Zobin and Mr. J. Sherin, AMEC, Canada and from Mr. F. Todd, True North, USA.

2. Condensate Flow Measurements

2.1 Piping Geometry and Flow Conditions

Main condensate line is located upstream of the deaerator and is a 24” nominal diameter carbon steel pipe with 0.4” nominal wall thickness. The flow rate variation from unit to unit is from 936 l/s to 979 l/s. Water temperature is approximately 130^0C and the variation from unit to unit is within 1^0C. Pressure variation from unit to unit is from 487 kPa to 564 kPa. Average flow parameters for each loop during data collection are shown in Table 1.

The section of the piping, where ultrasonic meters were located, is shown in Figure 1. It consists of three out-of-plane elbows followed by a vertical run. To achieve the required uncertainty, two separated ultrasonic transducers with three sets of ultrasonic probes on each transducer were installed at a close distance from each other on the vertical section of the pipe (Figure 2) and at distance of approximately 16 pipe diameters downstream of the closest upstream elbow.

Table 1. Average Flow Parameters During Flow Measurements

Unit ID	Data Collection Time (h)	ASME Nozzles Flow Reading (l/s)	Water Temperature ^{0}C	Pressure kPa	Reynolds Number (10^6)
Unit A	106	954.0	130.6	564.3	9.0
Unit B	40	971.2	130.8	535.8	9.3
Unit C	70	979.2	130.0	487.5	9.3
Unit D	38	936.0	129.2	518.1	8.8

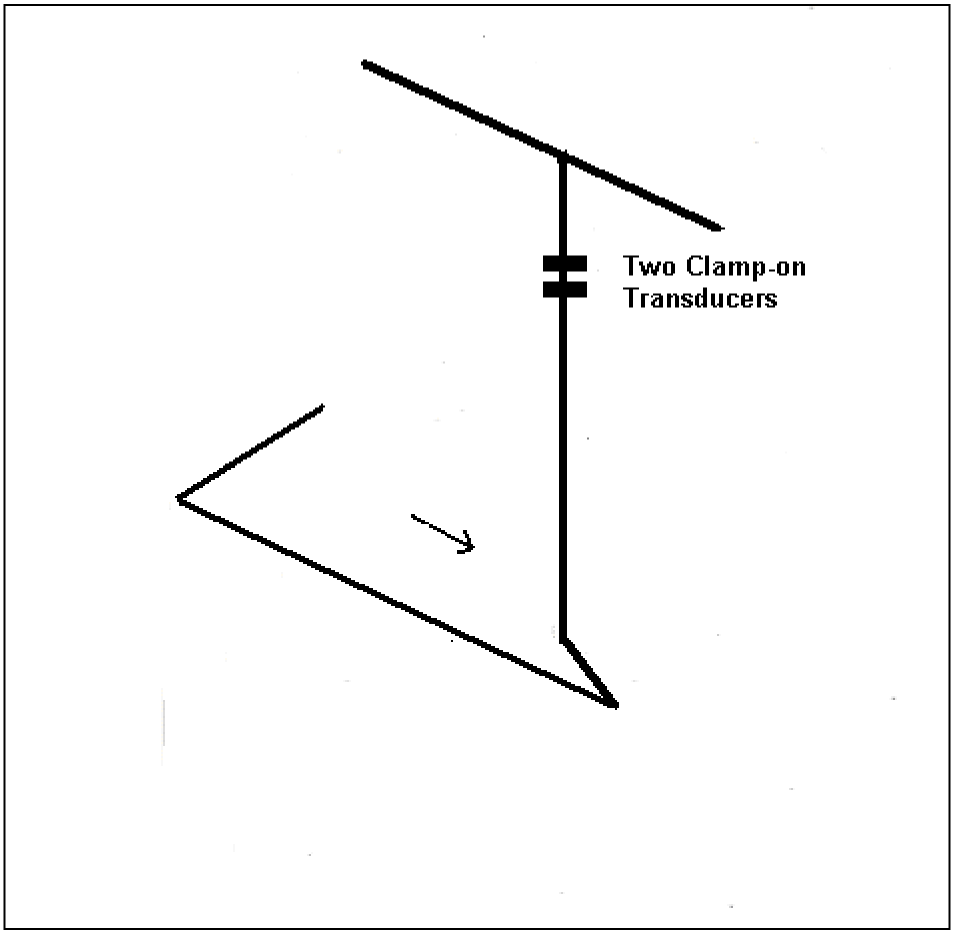

Figure 1. Piping Configuration and Location of Clam-on Meters

2.2 Required Uncertainty

The objective of the measurements was to verify the calibration of the ASME nozzle in each line. The ASME nozzles were originally calibrated and installed in early 1980's in 2006 one of the nozzles was inspected and was found in excellent condition. The PTC-6 Code (Guidance for Evaluation of Measurement Uncertainty in Performance Tests of Steam Turbines) specifies the uncertainty of the inspected nozzle as 0.35%. To verify that the other three nozzles' calibration was still valid, it was decided to compare their readings with the flow measurement results of clamp-on flow meter.

The analysis of the piping configuration upstream of the available location for the transducer installation showed that the upstream elbows could affect the ultrasonic flow readings. However, for this particular application high absolute accuracy was not required because it was sufficient to use the ultrasonic flow meter readings for a relative comparison with the ASME nozzles. Based on the assumption that if the location of the transducer is identical for each of the four pipes, the effect of the upstream disturbances on the flow readings will also be identical, the meter readings were not corrected for the specific piping configuration.

To achieve the goal of verifying calibration of ASME nozzles, it was necessary to achieve the uncertainty in the ratio of ASME nozzle readings to ultrasonic meter readings of better than 0.5%. As the transducers had to be moved from pipe to pipe four times, portable transducer design was used. The uncertainty component associated with transducer installation for the portable design is significantly higher than for a permanent transducer design and is close to 0.5%. To reduce this uncertainty two identical transducers were used, and each transducer had three sets of ultrasonic probes (See Figure 2 and 3), so that three separate sets of readings could be obtained from each transducer simultaneously. Thus, the readings of the each ASME nozzle were compared with the average of six readings from the ultrasonic meter. Averaging of three readings for each transducer with different angular positions of the ultrasonic beams was used to minimize possible scatter in the actual flow in each pipe. Comparison between the readings of two transducers was used to confirm the estimated uncertainty due to the transducer installation and to reduce the total uncertainty of the average value.

The pipe cross-section area at the transducer location was obtained by measuring the outer circumference and the wall thickness of the pipe in 24 points for each location. Water temperature was measured independently of plant instruments by platinum resistant thermometers using spare thermal wells adjacent to those used by the plant instruments. Pressure readings were taken from the plant instrumentation.

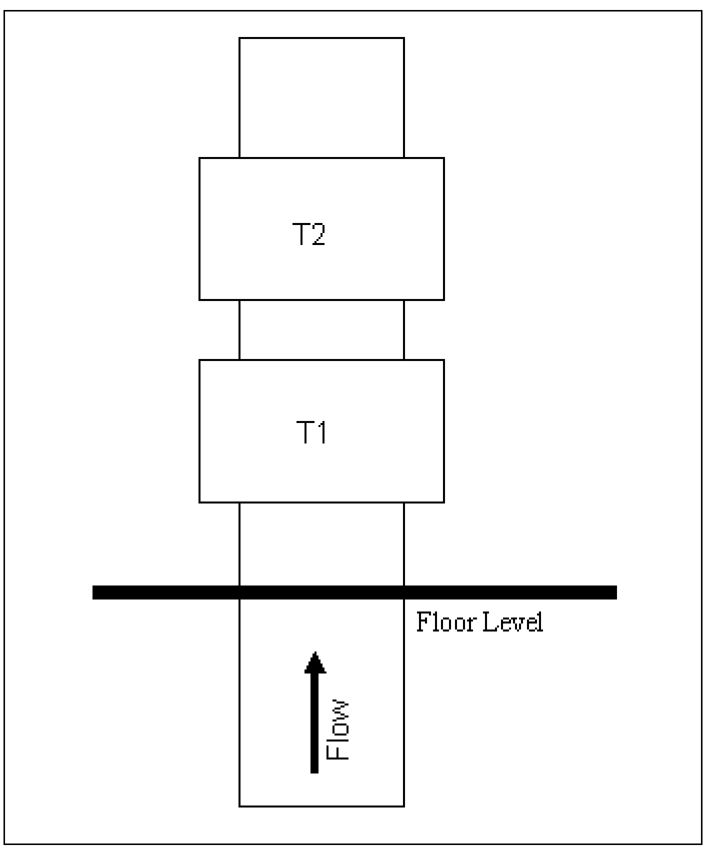

Figure 2. Position of Two Clamp-on Transducers on the Pipe

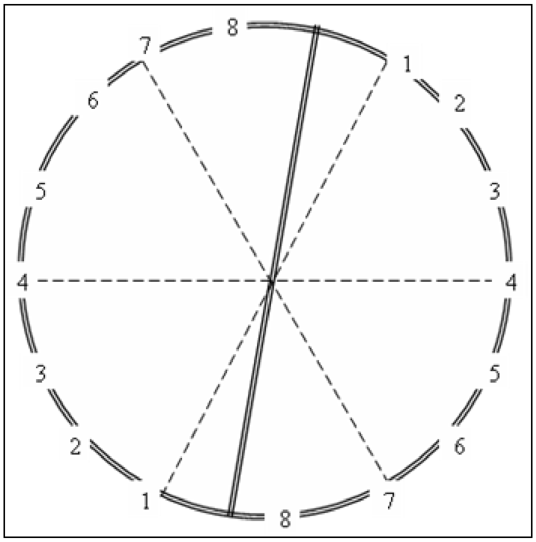

Figure 3. Dash Line Shows Positions of the Three Ultrasonic Beams

Estimations for the uncertainty components of the ultrasonic meter with a portable transducer and a single set of ultrasonic beams is presented bellow.

$\varepsilon_R = 0.5\%$	Repeatability to installation for a single beam reading
$\varepsilon_\tau = 0.16\%$	Time delay uncertainty – τ
$\varepsilon_L = 0.06\%$	Spacing between ultrasonic beams – L
$\varepsilon_A = 0.12\%$	Pipe cross-section area – A
$\varepsilon_\rho = 0.07\%$	Flow density – ρ

The total uncertainty for one set of beams:

$$\varepsilon_{SingleBeam} = \sqrt{\varepsilon_c^2 + \varepsilon_\tau^2 + \varepsilon_L^2 + \varepsilon_A^2 + \varepsilon_\rho^2} = \sqrt{0.5^2 + 0.16^2 + 0.06^2 + 0.12^2 + 0.07^2} = 0.55\%$$

The total measurement uncertainty for one portable transducer with three sets of ultrasonic beams has a reduced uncertainty because installation repeatability, spacing uncertainty and statistical uncertainty of the time delay measurement are independent:

$$\varepsilon_{ThreeBeamsMeter} = \sqrt{\frac{\varepsilon_c^2}{3} + \frac{\varepsilon_\tau^2}{3} + \frac{\varepsilon_L^2}{3} + \varepsilon_A^2 + \varepsilon_\rho^2} = \sqrt{\frac{0.5}{3}^2 + \frac{0.16}{3}^2 + \frac{0.06}{3}^2 + 0.12^2 + 0.07^2} = 0.34\%$$

Uncertainty of the average reading of two transducers with three sets of beams each is estimated as 0.24%.

Combining uncertainty of the ASME nozzle of 0.35% with uncertainty of the average readings of the cross-correlation meter of 0.24%, the uncertainty in the ratio of the flow readings of the two instruments is estimated as 0.42%.

2.3 Test Results and discussion

The ratio of the flow readings of ASME nozzle meters to the average flow readings of the two 3-beams ultrasonic meters for each pipe is shown in Figure 4. This ratio varies between 1.0116 and 1.0170 with the average value over all four pipes of 1.0147.

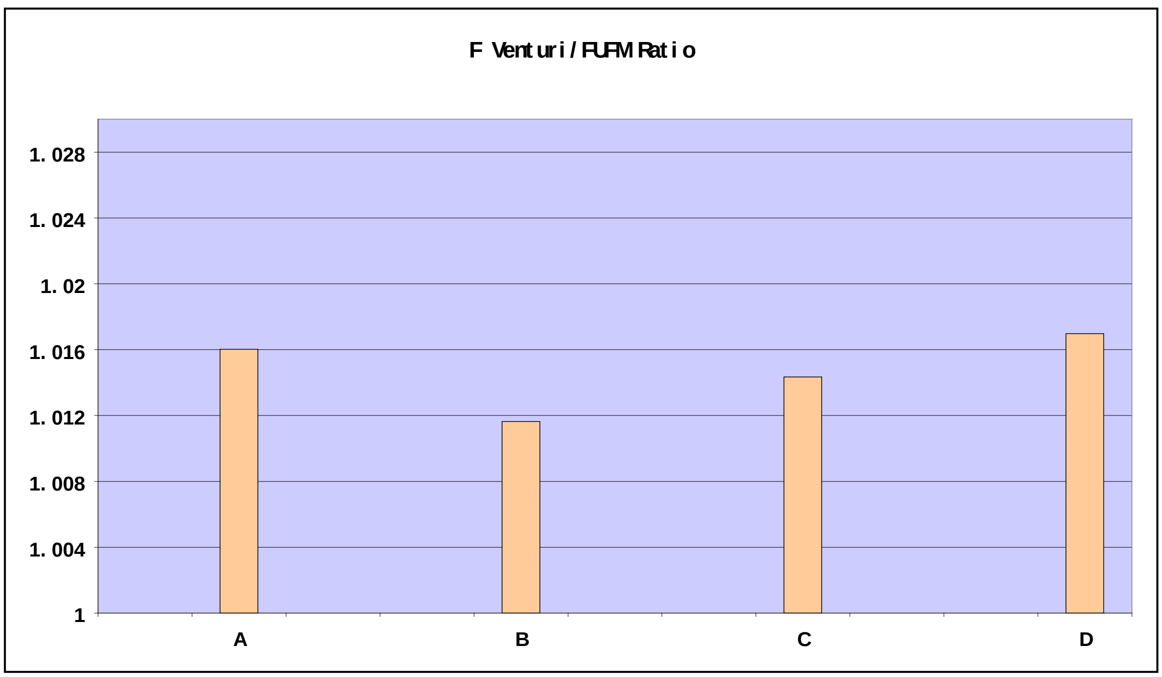

Figure 4. Ratio of ASME Nozzles Readings to Clamp-on Meters Readings for Each Pipe. Ultrasonic flow meter readings are not corrected for the piping geometry

The following observations can be made based on these results.

- The fact that the average ratio is higher than 1 by 1.47% is an indication of the effect of upstream piping geometry on the ultrasonic flow meter. This value is consistent with the results of previously conducted tests with a similar type of piping configurations.

- The difference in the ratio for different pipes is well within the expected estimated uncertainty of $\pm$0.42%. Deviation of the ratio from its average value of 1.47% for each pipe is shown in Figure 5.

2.4 Conclusion

Comparison of two different flow measurement technologies on four identical industrial pipes with pipe diameter 24", water temperature about 130^{0}C and Reynolds Number of 9 millions was a unique opportunity to verify both ASME nozzles and the clamp-on ultrasonic cross-correlation meter at flow conditions not available in a laboratory.

In spite of identical piping configuration and similar locations of the transducers in each of the units, it is still unlikely that velocity profiles and characteristics of turbulence are also identical in each pipe. Moreover, considering the actual difference in the flow rate, temperature and pressure, it is most likely that flow disturbances at the location of the transducer are not identical. However, consistency of the ratio of the flow readings of both types of flow meters shows that neither of them is sensitive to the actual differences in flow disturbances in different Units within the uncertainty of the measurements.

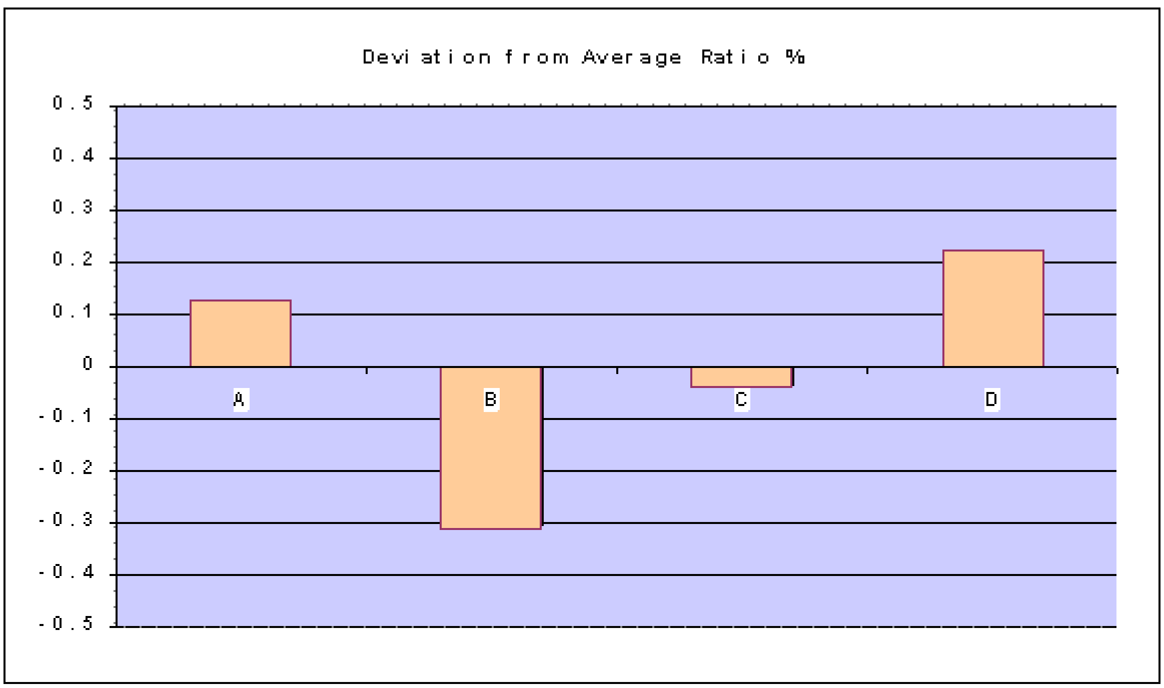

Figure 5. Deviation of Ratio from Its Average Value for Each Pipe.

3. Diesel Cooling Water

3.1 Piping Configuration and Test Description

The second example of application of clamp-on cross-correlation flow meter describes flow measurements in the Diesel Cooling Water (DCW) supply line.
The piping configuration of the DCW supply line is shown in Figure 6. It is a 10" carbon steel pipe with available location for the transducer installation at a distance of 14.8 pipe diameters downstream of a combination of a T-Junction and a 90-degree elbow.

The hydraulic effect produced by this specific piping configuration on the ultrasonic flow meter was never investigated before. Therefore it was decided to measure the flow rate in the DCW line in two separate locations: first by measuring the flow in this line directly by the ultrasonic flow meter, and secondly, by measuring the flow in the 24" and 20" lines upstream and downstream of the DCW line, as shown in Figure 1. To achieve that, three clamp-on transducers were installed, and the measurements were conducted in two steps.

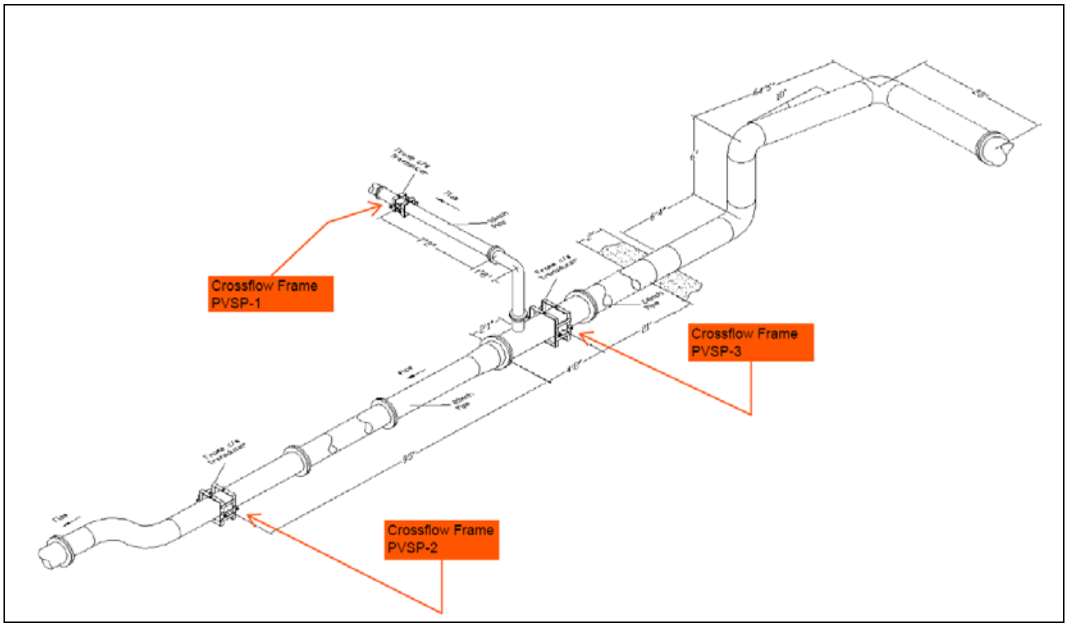

Figure 6: Piping Configuration and Location of the CROSSFLOW Transducers

In the first step, the DCW line was isolated, such that flow rate in 24" and 20" lines was the same. Flow readings from the 20" line was considered as a reference because clamp-on transducer was installed at a distance of more than 60 pipe diameters downstream of the nearest upstream disturbance, and the correction factor for flow measurements on a 24" pipe was derived. In the second step, the flow in the 10" pipe was restored to its normal value and the flow was measured in three locations as shown in Figure 1.

With such a set-up, the DCW flow was determined by two separated methods: as a difference between flow rates in 24” and 20” lines, and as an independent measurement.

The exact positions of the clamp-on transducers are shown in Table 2.

Results of the measurements in the first step are shown in Table 3.

Table 2. Exact positions of the clamp-on transducers

Meter Location (see Figure 2)	Pipe Length from Disturbance (inches)	Pipe Internal Diameter (inches)	Length Divided by Diameter From Disturbance
PVSP-1	86	10	8.6
PVSP-2	1165	19	61.4
PVSP-3	340	23	14.8

Table 3. Step One, Calibration Results

Flow Reading on 20” pipe (Reference Flow Reading)	16041.7 GPM
Not Corrected Flow Reading on 24” Pipe	15645.4 GPM
Correction Factor for 24” Pipe	1.0253

The value of the correction factor for the 24” pipe of 1.0253 shows that the effect of the flow disturbance on the clamp-on meter installed at a distance of 8.6 pipe diameters downstream of the combination of out-of-plane elbows is 2.53%, which is consistent with previously conducted laboratory tests on similar type of piping configurations.

The results obtained on the second step, with the normal flow in the DCW line, are shown in Table 4.

.

The flow rate in 10” pipe is approximately ten times smaller than flow rate in 24” and 20” pipes. However when flow rate in 10” pipe is calculated as a difference of flow rates in 24 “and 20” pipes, its uncertainty is only 2.8%, which is not ten times higher comparing with uncertainties in 24” and 20” pipes (See Table 4). Significant reduction of the uncertainty in the difference of two high flow rate flows is possible because calibration conducted in the first step reduces the number of independent parameters in calculation of the difference.

The uncertainties of independent flow measurements on DCW line (2.1%) and in 24” and 20” pipes is also higher than usual because of the uncertainty in the pipe cross-section area due to Plasite® liner on the inside surface of the pipes.

Table 4. Step Two, Independent Flow Measurement

20" Line Measured Flow (GPM)	**14743**	Uncertainty 1.1%
24" Line Measured Flow with no Correction for Specific Piping Geometry	15940	
24" Line Corrected Flow with Hydraulic Factor 1.0253 (See Table 4)	**16335**	Uncertainty 1.4%
10" (DCW) Line Flow Calculated as a Difference of 24” Line and 20” Line Flow Rates	**1592**	Uncertainty 2.8%
10" Line Independent Flow Measurement with no Correction for Specific Piping Geometry	**1549**	Uncertainty 2.1%

3. 2 Conclusions

Example 2 is an illustration of how multiple installations of a clamp-on meter can be used to measure flow affected by the upstream piping configuration.

An interesting element of this particular measurement is that the target flow is a branch of a major pipeline with the flow rate approximately ten times higher than the flow in the branch. The branch pipe flow rate was calculated as a difference between two larger flows one upstream and another downstream of the branch line. Irrespective of that, the final uncertainty of the branch flow rate was comparable with uncertainties of much higher measured flow rates in the major pipeline. Such reduction of the uncertainty was possible due to prior measurements of the flows in main line upstream and downstream of the branch pipe, when branch pipe flow was zero.

4. References

[1] M. S. Beck and A. Plaskowski, “Cross Correlation Flowmeters – their Design and Applications”, Adam Hilger, Bristol, 198

[2] Y. Gurevich, A. Lopez, R. Flemons, D. Zobin, “Theory and Application of non-invasive ultrasonic cross-correlation flow meter in harsh environment”, Proceedings of FLOMEKO 98, Lund, Sweden, 1998

[3] P.D. Lysak, D.M. Jenkins, D.E. Capone, W. L. Brown, “Analytical model of an ultrasonic cross-correlation flow meter, part 2”, Flow Measurement and instrumentation 19, 2008, pp. 41-46