Application of CROSSFLOW™ meter for feeder flow monitoring in CANDU plants

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1. Introduction

Obtaining accurate flow measurements in feeder pipes present a significant challenge. Flow measuring devices must operate under harsh environments involving high temperatures and high radiation fields. These devices must be able to operate reliably under such conditions for extended periods of time with the reactor in operation, and when any access to primary site instruments in the radiation area is restricted.

The CANDU utilities are looking for an accurate flow monitoring system that can provide independent flow measurements on selected Emergency Coolant Injection (ECI) channels, Shutdown System (SDS1 & SDS2) channels, Fully Instrumented channels (FINCH), or any other reactor feeder channels to assist in determining the accuracy of existing station instrumentation.

CROSSFLOW™ ultrasonic flow measurement device is a system capable of accurate flow monitoring using a non-intrusive, clamp-on system, which provides continuous monitoring of feeder flows at operating conditions.

2. CROSSFLOW™ Theory

Beginning with the first principles, this section develops the equations used by the CROSSFLOW™ meter to measure flow in a pipe.

Flow in a pipe is defined by the equation:

$$W = \rho A V_a \qquad (1)$$

where is W is the mass flow rate, ρ is the density of the fluid, A is the area of the pipe cross-section, and V_a is the average velocity of the fluid in the pipe within the cross-section.

A cross-correlation meter measures the time that it takes for turbulent eddies within the fluid to pass between two ultrasonic beams that are perpendicular to the axis of the pipe and also the flow stream. By knowing the physical distance between these two beams, the velocity of eddies within the flow stream can be calculated, as can the velocity of the fluid that contains them.

$$V_m = L/\tau \qquad (2)$$

Where V_m is the measured velocity, which is the average velocity of eddies in the pipe tracked by the cross-correlation meter, L is the physical distance between the two ultrasonic beams, and τ is the time it takes for eddies to pass between the two beams.

The measured velocity, V_m, is not equal to the average velocity, V_a, of the fluid in the cross-section. Hence, the measured velocity, V_m, must be multiplied by a correction factor, C_0, to obtain the average velocity of the fluid in the pipe.

$$V_a = C_0 V_m = C_0 (L/\tau) \qquad (3)$$

Substituting (3) into (1) gives the flow equation for the cross-correlation meter:

$$W = C_0 \rho A L / \tau \qquad (4)$$

The C_0 parameter of correction factor for a smooth straight pipe [1,2] and non-standard piping geometry was obtained by experiments.

3. Technology Validation

Most of the CROSSFLOW™ calibration has been done on feedwater pipes greater than diameter 12 inches, and the claimed accuracy was better than 0.5%. Since the technique was being successfully applied to feeder flow measurements and since the CROSSFLOW™ technology was the only method available for independent measurements of feeder channel flows, Ontario Hydro has performed validation of CROSSFLOW technology [3].

3.1 Validation Methodology

Validation was carried out as a series of "blind tests" with unknown actual flow values. The tests were conducted over a wide range of Reynolds Numbers, covering also the plant conditions. The range of Reynolds Numbers was achieved by varying the flow velocity, and by changing the fluid temperature varying from 16°C to 265°C. The validation was performed by comparing the CROSSFLOW™ data with laboratory reference flows in carbon steel pipes, length greater than 10 feet and nominal diameter of 3 inch.

3.2 Validation Results

The validation results of the CROSSFLOW™ technology are illustrated in Table 1.

All the CROSSFLOW™ readings, except one at the OPG Flow Testing Laboratory and one at the Stern Laboratories are within 1% of the reference flow. The average of the differences is 0.4% at the OPG Flow Testing Laboratory, -0.4% at the Stern Laboratories at 75° C, and +0.45% at 265°C, which is well within the combined uncertainty claimed for the CROSSFLOW™ meter and for the reference flow. (The combined uncertainty equals the square root of the sum of the squares (SRSS) of CROSSFLOW™ and the reference flow, i.e. $\sqrt{(0.95)^2+(0.25)^2}=0.98\%$.) These numbers confirm that on typical feeder pipes with a long straight section and typical feeder flow conditions (temperature, pressure, and Reynolds Number) CROSSFLOW™ can achieve accuracy better than 1% using standard installation procedures. See [3] and [4] for the original OPG Report validating CROSSFLOW™'s 1% accuracy in feeder pipes.

Table 1: Comparison of CROSSFLOW™ measurements with laboratory reference flows

Crossflow Readings (kg/s)			Laboratory Reference Flow (kg/s)	Difference (%)		
OPG Flow Testing Laboratory (16°C)						
Transducer T1	Transducer T2	Transducer P		Transducer T1	Transducer T2	Transducer P
16.579	16.634		16.60	+0.1	-0.2	
15.583	15.618		15.55	+0.2	+0.4	
15.165	15.206		15.18	+0.1	-0.1	
14.227	14.272		14.18	+0.3	+0.6	
13.086	13.151		13.00	+0.7	+1.2	
15.139	15.204		15.12	+0.1	+0.5	
15.179	15.199		15.12	+0.4	+0.5	
14.809	14.822		14.73	+0.5	+0.6	
13.989	13.981		13.89	+0.7	+0.7	
Stern Laboratories (75°C)						
30.892	30.939		30.963	-0.2	-0.1	
21.972	21.947		22.035	-0.3	-0.4	
32.903	32.456	33.050	32.906	0	-1.4	+0.4
32.914	32.901	32.484	32.895	+0.1	0	-1.1
32.547	32.707	32.650	32.845	-0.9	-0.4	-0.6
Stern Laboratories (265°C)						
28.182	28.139		28.026	+0.6	+0.4	
27.507	27.639		27.462	+0.2	+0.6	
Alden Research Laboratory (45°C)						
28.52		28.83	28.60	-0.3		+0.8
31.04		30.92	30.92	+0.4		0
48.23		48.11	48.20	+0.1		-0.2

3.3 Uncertainty Analysis

The typical uncertainty values used for the calculation of the total uncertainty of flow measurements for CANDU feeders are shown in Table 2. All of the uncertainties are based on a 95% confidence interval. This corresponds to a two standard deviation interval for components that were calculated from a large number of data points. For data sets that have less than 30 entries, a Student-t distribution was used for a 95% confidence interval.

Table 2: Typical uncertainty for feeder applications

Estimated Uncertainty of the Full Power Flow Measurement for Standard Feeder Installations								
Channel location	εA_T (%)	ε C_f Random (%)	ε C_f Bias (%)	$\varepsilon\rho$ (%)	εL_T (%)	$\varepsilon\tau$ Electronic (%)	$\varepsilon\tau$ File (%)	εQ (%)
Horizontal	0.500%	0.559%	0.000%	0.250%	0.040%	0.500%	0.150%	0.95%

εA_T (%): uncertainty of pipe cross-section area

εC_f Random (%): uncertainty in the flow correction factor [5].

εC_f Bias (%): The upstream geometry features cause perturbation from known values of the flow correction factor for a straight, smooth pipe. For a straight, smooth pipe, this uncertainty component is equal to 0%.

$\varepsilon\rho$ (%): uncertainty in flow density

εL_T (%): uncertainty in ultrasonic beam spacing

$\varepsilon\tau$ Electronic (%): uncertainty caused by electronic and data processing elements.

$\varepsilon\tau$ File (%): statistical uncertainty of measured flow time delay

εQ (%): total flow uncertainty

$\varepsilon\tau$ Noise (%): uncertainty of the noise effect estimation.

For the CROSSFLOW™ application of CANDU feeder pipes, under favorable conditions, an uncertainty value of better than 1% can be achieved. In feedwater pipes, the accuracy of ±0.5% or better can be achieved since the pipe diameter is larger than feeder pipes.

4. Conclusions

The CROSSFLOW™ system provides the most accurate non-intrusive flow measurement instrument for use on CANDU feeder pipes. Reliable and low-risk feeder flow measurement system for CANDU feeder pipes has been developed with plentiful experience of one hundred CANDU feeder installations over ten years. CROSSFLOW™ enables owners to improve the overall operating efficiency of their plants and achieve higher return-on-investment.

REFERENCES

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