Calibration Tests of Pulse-Doppler Flow Meter at National Standard Loop

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Calibration tests of UdFlow, ultrasonic pulse-Doppler flowmeter, were conducted at the national standard loop in Mexico, CENAM (The Centro National de Metrologia) in order to evaluate the accuracy of the flowmeter. Four ultrasonic transducers are mounted on the surface of stainless steel piping circumferentially with the diameters of 100mm and 200mm to measure four velocity profiles. Figure 1 shows pipe arrangements at CENAM. Flow rates can be obtained by integrating each measuring line and taking the average of them. Air was injected at the upstream of measuring point for ultrasonic reflectors. Tests were conducted at five different flow rates with the Reynolds numbers between 200,000 and 1,2000,000. Tests were repeated six times at each flow rate to evaluate repeatability. In addition, the put-off and put-back test was carried out at 100mm piping with the flowrate of 3000 L/m to evaluate reproducibly. The values of the CENAM loop are based on the average of weighing time while those of the ultrasonic-Doppler flow velocity-profile flowmeter are based on the time average of instantaneous values. The calibration tests found a deviation better than 0.3% between the two devices in terms of the average of the values recorded by six rounds of each measurement. From the results of measurement conducted with Reynolds number varied, it was found that the overall average deviation between the two devices was better than 0.3%.

Keywords: ultrasonic-Doppler, velocity profile, flowmeter, industrial application, calibration

1 INTRODUCTION

The feedwater (FW) systems of a power plant are generally exposed to high temperature and/or pressure conditions within large pipes. Therefore, determining a profile factor (PF) under the same flow conditions and configurations as large pipe diameters and curve bends is impractical and results in certain errors in measurement. In fact, it is impossible at the present time to determine a PF by a high-precision calibration loop using a weighing method under such high temperature and pressure conditions as in the FW system. Consequently, the PF has to be determined with a Reynolds number (Re) within one order of magnitude of the actual plant. The conventional ultrasonic flowmeters as described below round off all indeterminate errors by a PF as described in Figure 1(1). To remove these errors, efforts are needed to eliminate the PF by determining flow rates based on the calculation of true flow profiles in the piping (2, 3). In order to achieve a highly accurate flow measurement, the measurement of a flow profile is required to eliminate the PF (4). We have conducted fields test using UDF, the flow-metering system by ultrasonic pulse-Doppler profile-velocimetry (5) where instantaneous flow profiles and flow rates were widely measured in CW systems and steel penstock of hydro-turbines, etc(3). The application for the nuclear FW measurement requires further high accuracy within 0.5% to monitor the thermal power and to utilize the measurement uncertainty for a power uprate. Integration of instantaneously-determined flow velocity profiles, obtained by performing continuous line-measurements over piping, will provide an accurate flow rate measurement system as an advanced flowmeter, superior to the conventional flowmeter using a PF. The conventional flowmeters based on the time-of-flight (TOF/transit time) method depend largely on the accuracy of a PF as it finally determines the flow rate of a fluid by multiplying it. This is also true of a one-point ultrasonic-Doppler flowmeter. Accordingly, these conventional methods are limited in the scope of application as they are effective only in measuring flows with steady-state developed flow. In other words, the methods have to use an approximation that is applicable only in a narrow flow range.(6)

Calibration tests were performed at the national standard loops in four countries. The UDF is based on the measurement of line velocity profiles, thereby eliminating PFs, resulting in a more accurate determination of flow rates.

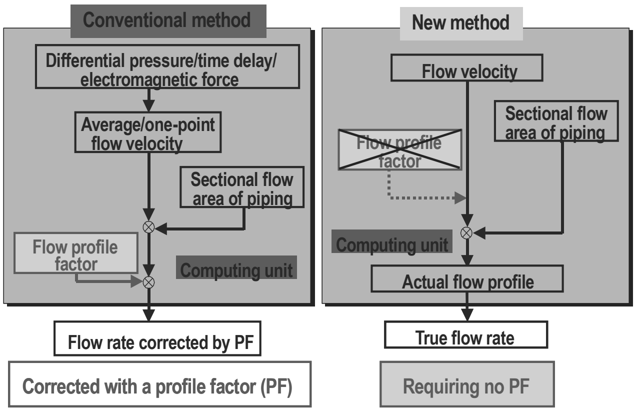

Figure 1. Conceptual comparison between conventional flowmeters and the flow-metering system by ultrasonic Pulse-Doppler profile-velocimetry.

2 CALIBRATION TESTS AT NIST, NMIJ, AND NMI

2.1 Tests at NIST

The flow rate of water per unit length of time can be determined by accumulating fluid flowing down the measuring test section into the weighing tank in a given period of time and dividing the volume of the fluid thus accumulated by the time elapsed. The nominal measurement error of the test loop at NIST is 0.12%. In these tests, the flow of water was measured at the point where it reached the stage of full development. The UDF was found to meet the approved values of the standard loop with sufficient accuracy. Table 1 compares the approved values of the NIST standard loop and the corresponding data on the UDF at Re = 400,000. The values of the NIST loop were based on the average of weighing time while those of the UDF were based on the time average of instantaneous values. As indicated in the table, the measuring test found a deviation of 0.03% between the two devices in terms of the average values recorded by five rounds of measurement. From the results of measurement conducted with varied Re numbers, it was found that the overall average deviation between the two devices was determined to be no more than 0.2% (7).

Table 1. Comparison of the approved values of the NIST standard loop.

Run No.	UdFlow	NIST	Deviation	
			L/s	%
#1	69.760	69.600	-0.161	-0.23%
#2	69.670	69.613	-0.057	-0.08%
#3	69.725	69.612	-0.113	-0.16%
#4	69.444	69.622	0.178	0.26%
#5	69.569	69.609	0.040	0.06%
Average	**69.634**	**69.611**	**-0.022**	**-0.03%**

2.2 Tests at NMIJ and NMIT

Further calibration tests were conducted on the UDF by a liquid flowmeter calibration facility, a verification loop, at NMIJ in Japan and NMI in the Netherlands.

The calibration tests on the UDF were carried out for water with a measuring instrument attached to the 400A piping section of the loop at NMIJ. At NMI, the calibration tests were carried out for water and kerosene with the 150A piping section of the loop. Both calibration facilities (made to the national standard loop) have the standard uncertainty set at 0.02% of the reference flow rate. The results of the test at NMIJ and NMI are summarized in Table 2 and Table 3, respectively.

Table 2. Comparison of the approved values of the NMIJ standard loop.

Reference Flowrate Q_1 (m^3/h)	Output of Flowmeter under Test Q_{fn} (m^3/h)	Ratio of Flowrate and Uncertainty	
		Ratio Q_{fn}/Q_1	Expanded Uncertaintly (k = 2)
2000.5	2008.9	1.004	0.4%
1512.7	1508.2	0.997	0.1%
986.1	984.6	0.999	0.3%

The test findings indicate the uncertainty of the flowmeter examined in terms of the average of the results recorded in 10 rounds of measurement at NMIJ and three rounds at NMI, comparing with the reference flow rate set as a target. The reference meter of NMIJ was based on a weighing method, and that of NMI was a turbine flowmeter. Based on these measuring tests, the UDF was given a calibration certificate showing uncertainty ranges within 0.4% at NMIJ and 0.59% at NMI for water.

2.3 CALIBRATION TESTS at CENAM

Following improvements to the UDF System, calibration tests were carried out at CENAM, using ultrasonic transducers clamped on the surface of stainless steel piping having diameters of 100 mm and 200 mm.

Table 3. Comparison of the flow rates measured by UDF with the approved values of the NMI standard loop for water (left) and kerosene (right).

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Reference Flow-rate [l/min]	Reference Velocity [m/s]	Indicated Flow-rate [l/min]	Indicated Velocity [m/s]	Deviation [%]
1276.7	1.2041	1273.1	1.2007	-0.28
1276.6	1.2040	1280.7	1.2079	+0.32
1276.8	1.2042	1271.7	1.1994	-0.40
953.76	0.8995	959.4	0.9048	+0.59
953.41	0.8992	952.8	0.8986	-0.07
953.74	0.8995	949.1	0.8951	-0.49
632.02	0.5961	633.9	0.5979	+0.30
631.82	0.5959	628.5	0.5928	-0.52
632.04	0.5961	630.1	0.5943	-0.30

Reference Flow-rate [l/min]	Reference Velocity [m/s]	Indicated Flow-rate [l/min]	Indicated Velocity [m/s]	Deviation [%]
1276.6	1.2040	1279.5	1.2067	+0.22
1276.4	1.2038	1281.3	1.2084	+0.38
1276.5	1.2039	1281.5	1.2086	+0.39
956.19	0.9018	949.3	0.8953	-0.72
956.54	0.9022	959.1	0.9046	+0.27
955.92	0.9016	955.4	0.9011	-0.06
639.51	0.6032	641.1	0.6046	+0.23
639.49	0.6031	643.6	0.6070	+0.65
639.30	0.6029	643.90	0.6073	+0.73

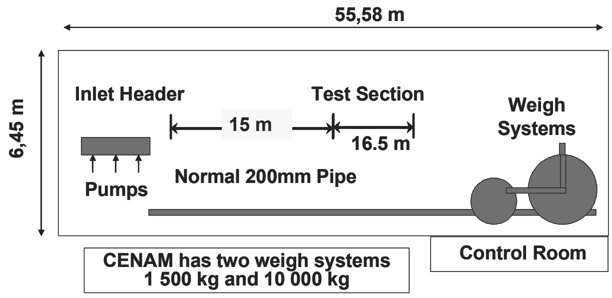

Figure 2.CENAM Water Flow Lab Layout-Normal 200mm Diameter Test

Figure 2 shows the pipe arrangement at CENAM. The CENAM loop contains a straight pipe long enough to produce the developed flow condition, an inlet header and pumps, and weigh systems. CENAM has two weigh systems of 1,500 kg and 10,000 kg.

Air was injected upstream of the measuring point up to ~400 ppm (0.04% as a volumetric fraction.). We confirmed that there was a negligible effect of air injection on the flow rates measured by the weigh systems of CENAM, comparing the flow rate measured without air injection with one using air injection.

Tests were conducted at five different flow rates with the Reynolds numbers between 200,000 and 1,330,000. Tests were repeated six times at each flow rate to evaluate repeatability. In addition, the take-off and put-back test was carried out on the 100 mm piping with the flow rate of 3000 L/m to evaluate reproducibility. The values of the CENAM loop are based on the average of weighing time while those of the UDF were based on the time average of instantaneous values. The references 8, 9, and 10 provide the following definitions of each Individual Value :

2.3.1 Relative Errors

The relative error between *qv* from the reference and *qv* from the meter is defined by:

$$e = \left(\left[\frac{qv_{meter}}{qv_{\ primary\ standard}} \right] - 1 \right) 100 \qquad (\%)$$

2.3.2 Meter Factor

The Meter Factor (MF), $MF_i\ (q_j)$, for a single measurement *i* at flow q_j:

$$MF_i(q_j) = \frac{qv_{j\ \ primary\ standard}}{qv_{j\ \ meter}}$$

where, :

$qv_{primary\ standard}$ – volumetric flow-rate determined by the primary standard at line conditions (L/min).

$qv_{\ meter}$ - time-averaged volumetric flow rate measured for the meter, at line conditions, over the calibration interval (L/min).

The MF arithmetic mean value for a series of measurements at the flow rate q_j :

$$\overline{MF_j}\ (q_j) = \ \overline{MF}_j\ = \frac{1}{n}\sum_{i=1}^{n} MF_i(q_j)$$

2.3.3 Meter Factor Uncertainties

The experimental variance of $MF_i\,(q_j) = s^2(MF_j)$, from repeated measurements at flow rate q_j:

$$s^2\left(MF_j\right) = \frac{1}{\text{n-1}}\sum_{i=1}^{n}\left(MF_i(q_j) - \overline{MF_j}(q_j) \right)^2$$

The experimental standard deviation of the mean of the Meter Factor, $sdm(\overline{MF_j})$ at each flow, is given by:

$$sdm\ \left(\overline{MF_j}\right) = \frac{1}{\sqrt{n}}\, s\left(MF_{\ j}\right)$$

where n is the number of the replicated tests at flow j. The meter Repeatability, i.e., the short term stability can be quantified as the experimental standard deviation of the mean at each test flow; the largest Repeatability is quoted as a bound for the meter for all of the flows tested.

2.3.4 Expanded Uncertainty

The Expanded Uncertainty, *U* is:

$$U\left(\overline{MF}_j\right) = \ kU_C\left(\overline{MF}_j\right)$$

The expanded uncertainty U can also be expressed using a coverage factor k based on t-distribution for ν_{eff} degrees of freedom with a level of confidence of approximately 95 %. This uncertainty was evaluated according to Reference 9.

2.3.5 Reproducibility

For specific sets of tests done for the UDF, Reproducibility is defined in terms of the standard deviation of the mean of the multiple sets of runs taken at essentially the same flow condition after specific, typical changes in test conditions are made to assess the meter's performance in these conditions. The specific changes made need to be described. Typical changes needed by most meter users are turning the flow off and then turning it back on, and then repeating the tests; this effect can be quantified by the TOTO (turn-off-turn-on) Reproducibility. For clamp-on type meters, another typical change is quantified by TOPB (take-off-put-back) Reproducibility. The conditions changed in these tests include, for a single flow, both TOTO and TOPB and the Reproducibility, i.e., longer term meter stability obtained is quantified by the experimental standard deviation of the mean for these tests:

Table 4 Summary data of the tests on the 100 mm pipe diameter and on the 200 mm pipe diameter in fully-developed flow conditions. The table below lists the mean values of MF -meter factor - and standard deviation calculated from 6 values, the Reproducibility (for a single flow) and the expanded uncertainty of the meter factor.

Primary Standard				UdFlow	Test Result	
Reynolds Number	Average Flow Velocity v (m/s)	Primary Standard Flow Rate qv (L/min)	Relative Standard Deviation s (%)	Meter Flowrate Qvm (L/min)	Meter Factor MF	Deviation e (%)
200 mm pipe diameter						
$4.46\cdot10^{5}$	2.1	4 000.73	$1.59\cdot10^{-2}$	4 010.06	0.997 68	0.23
$6.59\cdot10^{5}$	3.1	6 006.78	$1.64\cdot10^{-2}$	6 012.02	0.999 13	0.09
$8.93\cdot10^{5}$	4.1	8 005.22	$1.46\cdot10^{-2}$	7 998.56	1.000 83	- 0.08
$1.11\cdot10^{6}$	5.2	9 998.64	$1.36\cdot10^{-2}$	9 980.48	1.001 82	- 0.18
$1.33\cdot10^{6}$	6.2	12 002.10	$5.22\cdot10^{-3}$	12 011.41	0.999 23	0.08
$4.46\cdot10^{5}$	2.1	4 000.73	$1.59\cdot10^{-2}$	4 010.06	0.997 68	0.23
$6.59\cdot10^{5}$	3.1	6 006.78	$1.64\cdot10^{-2}$	6 012.02	0.999 13	0.09

$$R = sdm\left[\overline{MF}_j\right] = \sqrt{\frac{1}{m(m-1)}\sum_{i=1}^{m}\left[MF_i\left(q_j\right) - \overline{MF}_j\right]^2}$$

where “j” is the flow for which the “changed conditions” tests were done again and “m” is the total number of repetitions of data points taken at essentially the same test flow. Table 4 summarizes the test data on the 100 mm and 200 mm pipe diameters in fully-developed flow conditions. The average flow velocities varied from ~2m/s to ~6m/s for both pipes. The Reynolds numbers were set up to 1,330,000 for the case of the pipe diameter of 200 mm, and 641,000 for 100 mm. From the results of measurement conducted with varied Reynolds numbers, it was found that the overall average deviation between the two devices was better than 0.3%. The table lists the mean values of meter factor and standard deviation calculated from 6 values, the Reproducibility (for a single flow) and the expanded uncertainty of the meter factor.

3 CONCLUDING REMARKS

The calibration tests of UDF were conducted at four national standard loops: NIST in the United States, NMIJ in Japan, NMI in the Netherlands, and CENAM in Mexico, in order to evaluate the accuracy of this new type flow-metering system. The test results at NIST, NMIJ, and NMI for the velocity profile measurements exhibited the deviations within ~0.5%. Following improvements to the UDF System, the maximum spreads in individual MF test results in the mean values for the UDF are from −0.17% to +0.14 % for the 100 mm diameter pipe and from −0.18% to +0.23 % for the 200 mm diameter pipe over the range of Reynolds numbers tested at CENAM. At CENAM the short term stability (Repeatability) and longer term stability (Reproducibility) are both considered good, i.e., better than 0.03 % in these test conditions. Further testing needs to be done to better quantify Reproducibility characteristics.

The expanded uncertainty for the UDF Meter Factor in these tests at CENAM is bounded by ± 0.21 % for Test 1 (100 mm pipe) and by ± 0.16 % for Test 2 (200 mm pipe); these values are computed for 95% confidence levels. A negligible effect on the CENAM primary standard measurements was found for the air bubble injection used for these tests.

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