Series of Calibration Tests at National Standard Loops and Industrial Applications of New Type Flow-Metering System with Ultrasonic Pulse-Doppler Profile-Velocimetry for Power Plants

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Flow profile factors (PFs), which adjust measuring to real flow rates, also strongly depend on flow profiles. To determine profile factors for actual power plants, manufactures of flowmeters usually conduct factory calibration tests under ambient flow conditions. Indeed, flow measurements with high accuracy for reactor feedwater require them to conduct calibration tests under real conditions, such as fluid conditions and piping layouts. Moreover, as nuclear power plants are highly aging, readings of flowmeters for reactor feedwater systems drift due to the changes of flow profiles. The causes of those deviations are affected by the change of wall roughness of inner surface of pipings. Those changes of flow patterns lead to large errors in measurements with time-of-flight (TOF) ultrasonic flow meters. Therefore, we have to take into account those effects in order to measure the flow rates of feedwater with better accuracy in actual power plants. We proposed the new type of flowmeter called UdFlow/UDF, ultrasonic pulse-Doppler flowmeter, which can measure instantaneously-determined flow-velocity profiles and eliminate the effect of deviated flow profile from expected ideal one in measurements. Calibration tests of UdFlow/UDF were conducted at the national standard loop in Mexico, CENAM (The Centro National de Metrologia) and in USA, NIST (National Institute of Standard and Technology) 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. Flow rates can be obtained by integrating each measuring line and taking the average of them. A small amount of miniaturized air bubbles 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 ~1,200,000. 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 flow rate of 3000 L/m to evaluate reproducibly. The values of the CENAM and NIST loops 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%. The UdFlow/UDF system has been applied for the flow rate measurements in the circulation cooling water line of fossil-fired and nuclear power plants, and in the steel penstock of hydro-power plants. We are ongoingly carrying out the development of the UdFlow/UDF system for the application to nuclear feedwater flow rate measurements.

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

1 INTRODUCTION

With these concerns for accurate measurement of nuclear feedwater flow rates to gain uprated power by measurement uncertainty, time-of-flight (TOF) ultrasonic flowmeters are being introduced to nuclear power plants in the United States and Japan. However, these make it inevitable in quite a few measuring errors for large pipings in nuclear power plants due to unreliability of flow profile factors (PFs), because PFs used for existing nuclear power plants were experimentally obtained at much lower Reynolds Numbers with room temperatures and atmospheric pressures than half of actual ones, which were ~14,000,000 for the feedwater flow under ~7.6MPa and ~220deg-C in existing a boiling water reactor, and because the inner surface roughness of pipings changed by aging has not been taken into account for PFs used for existing nuclear power plants. Therefore, the measurement accuracy of flow rate by conventional time-of-flight ultrasonic flowmeters is questionable. The general discussion on these errors will be made as Facility Factor (1).

Figure 1 shows the changes in PFs due to the changes of pipe roughness. These calculations were done using the numerical simulation code, STAR-CD, and logarithmic law under the same hydraulic conditions as 480MW class reactor feedwater system (2). Two kinds of flowmeters were selected for the calculations of PFs, cross flow and transit time (time-of-flight: TOP) types. As the equivalent sand-grain surface roughness, Ks, gets rougher, PFs deviate with a few percentage points against the PFs of smooth pipings in both systems.

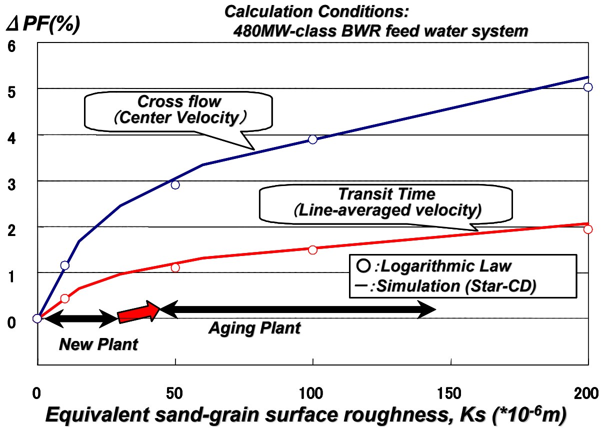

Figure.1 Percentage changes in Profile Factors vs. surface roughness

Up to around 6% deviation is observed in the case of cross flow measurement system that measures the centered-area velocity of pipings. In the case of transit time flowmeter, the PF deviates up to 3% against the smooth pipings. Therefore, if nuclear power plants get aging, we are supposed to experience those PF deviations in both systems. These deviations directly affect to the accuracy of flowmeters.

The feedwater (FW) systems of a power plant are generally exposed to high temperature and/or pressure conditions within large pipes. Therefore, determining the 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 PFs 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 2(3).

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 (4,5). In order to achieve a highly accurate flow measurement, the measurement of a flow profile is required to eliminate the PF(6). We have conducted fields test using the UDF System, the flow-metering system by ultrasonic pulse-Doppler profile-velocimetry(7) where instantaneous flow profiles and flow rates were widely measured in CW systems and steel penstock of hydro-turbines, etc. 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

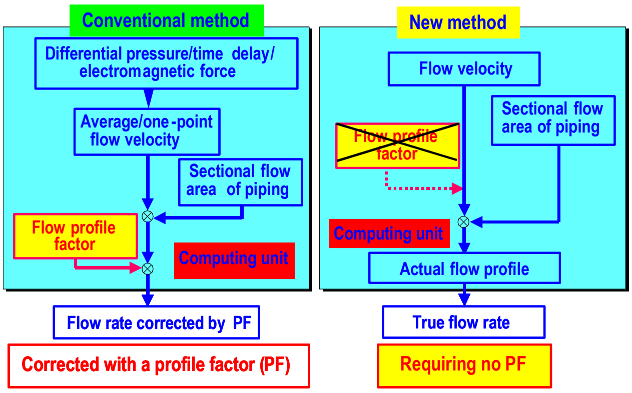

Figure2.Conceptual comparison between conventional flowmeters and the flow-metering system by ultrasonic Pulse-Doppler profile-velocimetry.

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(8) .

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.

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 layout of the NIST standard loop is shown in Figure 3. 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

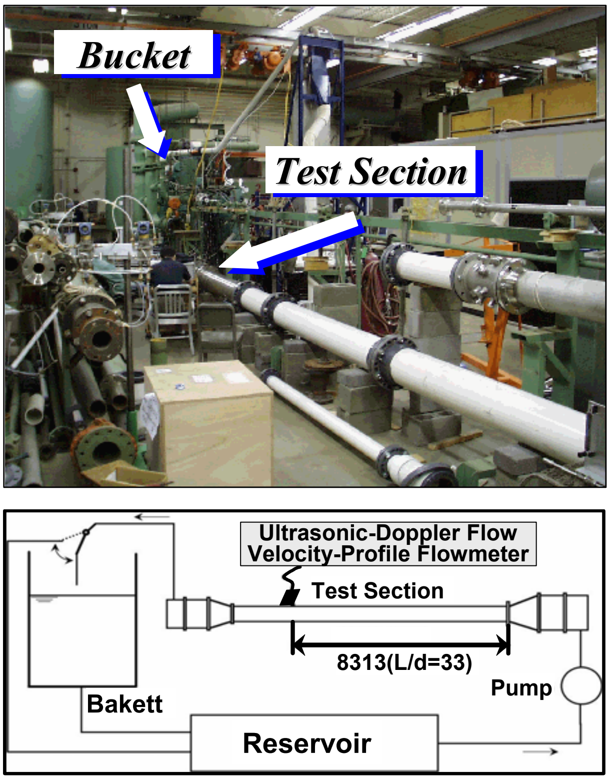

Figure 3. Layout of NIST standard loop

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% (9).

2.2 TESTS AT NMIJ AND NMI

Further calibration tests were conducted on the UDF by a liquid flowmeter calibration facility, a verification loop shown in Figure 4, at NMIJ in Japan, and NMI in the Netherlands shown in Figure 5 for the water loop and Figure 6 for the kerosene loop.

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.

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%

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%**

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.

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.

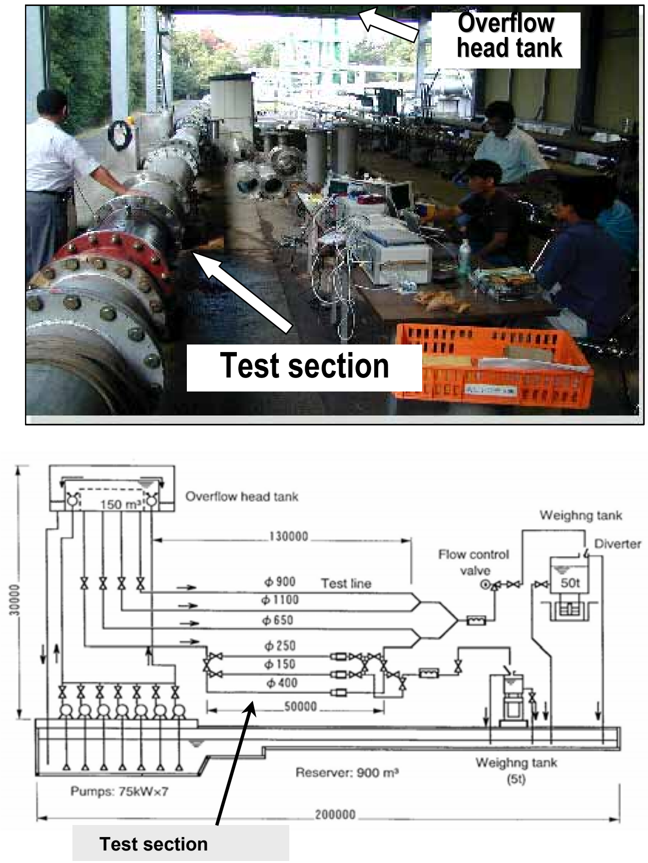

Figure 4. Layout of standard loop and test facility of 400mm pipe test in National Metrology Institute of Japan

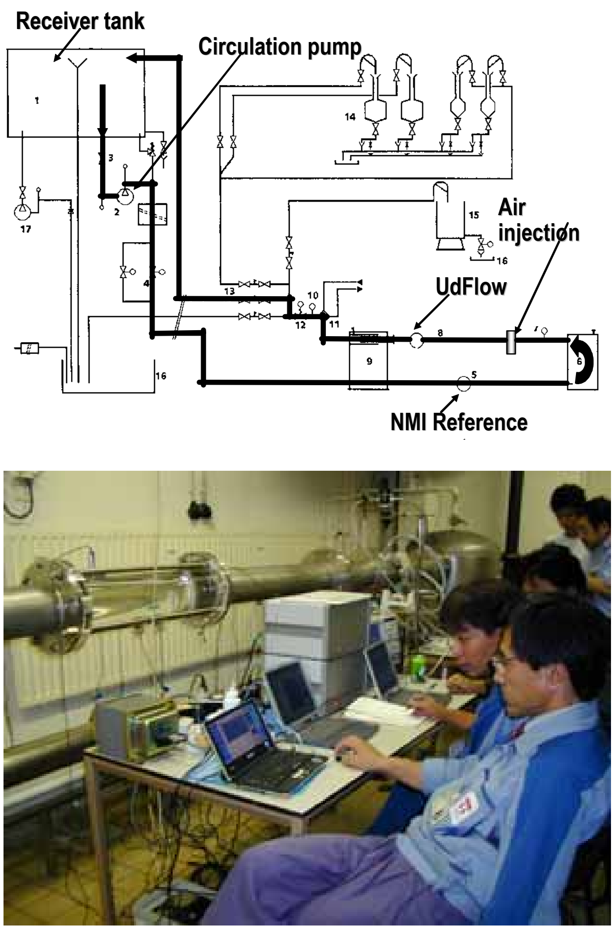

Figure 5. Layout of NMI standard loop for water

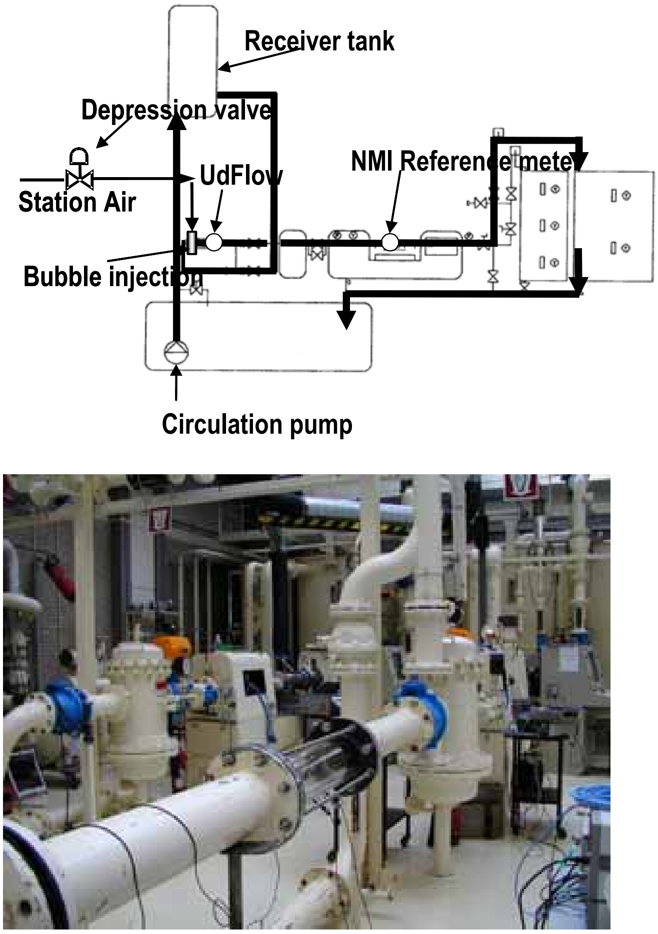

Figure 6. Layout of NMI standard loop for kerosene

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.

Figure 7 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

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). NMi - Nederlands Meetinstituut

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

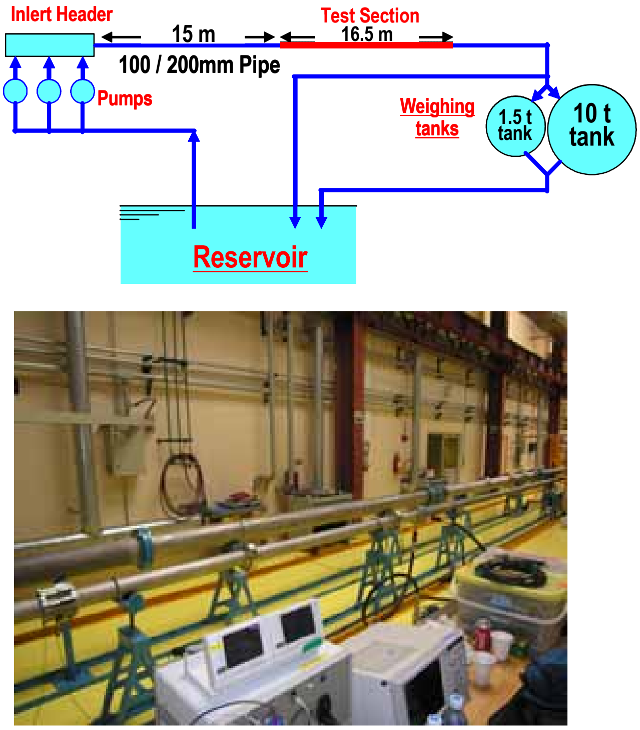

Figure 7 Layout of CENAM standard loop for water and pipe arrangement.

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:

3.1 RELATIVE ERRORS

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

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

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 :

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

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.

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.

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

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

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:

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

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.

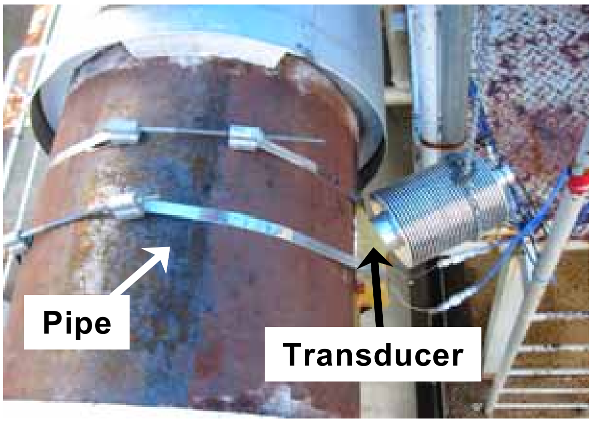

Figure 8 Measurement test section of nuclear feed water Conditions.

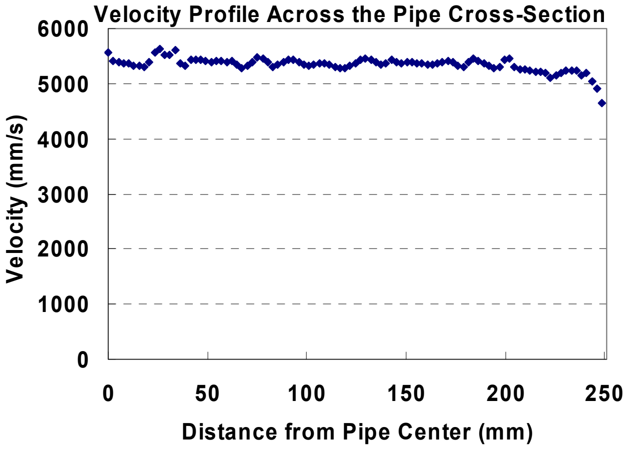

Figure 9 Velocity profile measured at actual nuclear feed water Conditions at high Reynolds number of ~14,000,000.

4 INDUSTRIAL APPLICATIONS

4.1 MEASUREMENT TESTS OF NUCLEAR FW CONDITIONS AT HIGH REYNOLDS NUMBER

Measurement tests were carried out to check the performance of the UDF system in elevated temperatures with high Reynolds numbers of

~14,000,000, which are corresponding to ones of feedwater conditions of a boiling water reactor. Figure 8 shows the measurement test section for nuclear reactor feedwater conditions. The ultrasonic transducer was mounted on the carbon steel pipe whose inner diameter of 500mm with the wall thickness of 29.0mm. The volumetric flow rate was ~3200m^3/h at temperature of 215deg-C and ~7.6MPa in pressure. The miniaturized helium gas bubbles were injected as reflectors with 40ppm in volume. Flow velocity profiles were successfully measured as shown in Figure 9. The averaged velocity was around 5m/s and the profile seemed relatively flat due to the measuring position of ~10D from a pipe bend.

4.2 FIELD MEASUREMENT TESTS IN A HYDRO-POWER STATION

Flow velocity profiles were measured to evaluate flow rates of a steel penstock in a hydro-power station. Figure 10 shows the overview of the measuring position and steel penstock. Two transducers were installed at the horizontal diameter position of 19D from the inlet of steel penstock, and two simultaneous measurements revealed that non axially-symmetry flow patterns existed at 19D from the inlet of steel penstock as shown in Figure 11$^{(10)}$. The average of two lines was 1.36 m^3/s with 1.39 m^3/s for the transducer A and 1.33 m^3/s for the transducer B.

4.3 FIELD MEASUREMENT TESTS IN A FOSSIL-FIRED POWER STATION

Figure 12 shows the overview of measuring test section at a sea circulation water pipe in a fossil-fired power station. The pipe diameter is ~1700mm with the wall thickness of 12.8mm. The velocity profile was obtained for the half in diameter, near

Figure 10 Overview of measurement test at a steel penstock in a hydro-power station.

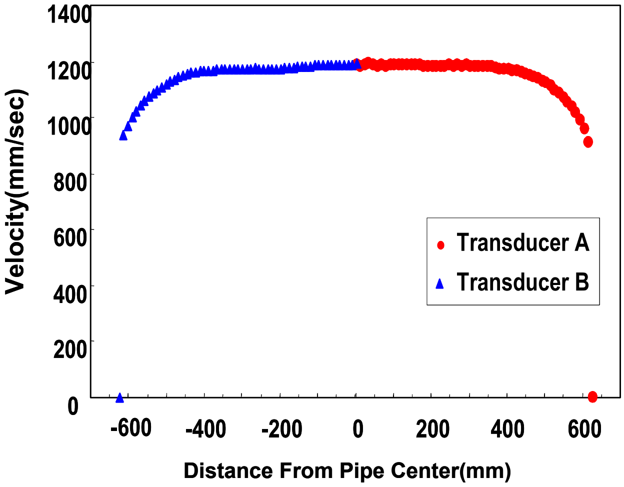

Figure 11 Measured velocity profiles at a steel penstock of ~1250mm in diameter in a hydro-power station.

Figure 12 Overview of measurement test at a sea circulation water pipe in a fossil-fired power station.

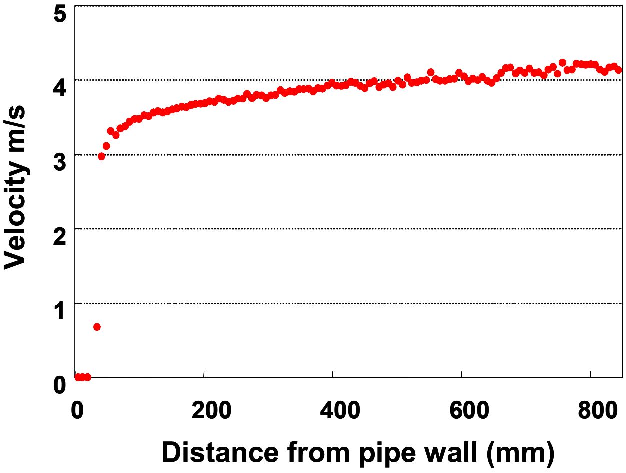

Figure 13 Measured velocity profile at a sea circulation water pipe of ~1700 in a fossil-fired power station.

side of the wall on which the ultrasonic transducer was clamped on, since the average velocity was ~4m/s with a flow rate of 10m^3/s and the diameter of ~1700mm, as shown in Figure 13, which resulted in constraint by the Nyquist theory.

5 CONCLUDING REMARKS

The calibration tests of the UDF System 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 may need 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 the test with 100 mm pipe and by ± 0.16 % for the test with 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.

Measurement tests for industrial applications were carried out in the high-temperature loop simulating nuclear reactor feedwater conditions, hydro-power station, and fossil-fired power station. The UDF System of new type flow-metering with ultrasonic pulse-Doppler profile-velocimetry has revealed its high applicability for elevated temperature conditions of nuclear reactor feedwater, the steel penstock of hydro-power, and the circulated water pipe in fossil-fired power plants.

REFERENCES

(1) Takeda, Y., "ON THE TRACABILITY OF ACCURACY OF ULTRASONIC FLOWMETER", ICONE-14 89803, Proceedings of ICONE 14, July 17-20, 2006, Miami, Florida USA

(2) Tezuka, K., et. al.,, "Industrial Applications of New Type Flow-metering System by Ultrasonic-Doppler Profile-Velocimetry, (1) Effects of Surface Roughness and Asymmetric Pipe Flow on Accuracy of Profile Factor", Fourth International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering, Hokkaido University, Sapporo, Japan, September 6-8, 2004

(3) Mori, M., et.al., "Industrial Application Experiences of New Type Flow-metering System based on Ultrasonic-Doppler Flow Velocity-Profile Measurement," Third International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering, EPFL, Lausanne, Switzerland, September 9 - 11, 2002

(4) Takeda, Y., et. al., "Development of flow rate measurement using ultrasonic Doppler method [1]Theoretical background," 1998 Fall Meeting of AESJ, [1998] F16, p.343

(5) Mori, M., et. al., "Development of ultrasonic-Doppler velocity profile method for flow rate measurements of power plant," [1999] ICONE-7, FP7429

(6) Mori, M., et. al., "EFFECTS OF INNER SURFACE ROUGHNESS AND ASYMMETRIC PIPE FLOW ON ACCURACY OF PROFILE FACTOR FOR ULTRASONIC FLOW METER," ICONE-14 89729, Proceedings of ICONE 14, July 17-20, 2006, Miami, Florida USA.

(7) Mori, M., et. al., "Development of a novel flow metering system using ultrasonic velocity profile measurement," Experiments in Fluids, 32 [2002] pp.153-160.

(8) Takeda, Y., "Measurement of velocity profile of mercury flow by ultrasound Doppler shift method," Nuclear Technology, 79 [1987]. pp 120-124.

(9) Takeda, Y., et. al., "Development of a new flow metering system using UVP, Preliminary performance assessments using NIST flow standards," Proceedings of ASME FEDSM'00, ASME 2000 Fluids Engineering Division Summer Meeting, June 11-15, Boston, Massachusetts.

(10)Suzuki, T., "Development of New Flow Metering System using Ultrasonic Doppler Method, (2)Flow-rate Measurement for Hydraulic-Turbine Efficiency at Hydroelectric Power Stations", ICEE2008, 90691, July 6-10, 2008, Okinawa, Japan.