Industrial Applications of New Type Flow-metering System by Ultrasonic-Doppler Profile-Velocimetry

(2) Measurement Experiences of Flow on Piping and Industrial applications

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

ABSTRACT

Electric power plants with thousands of flowmeters measure the flow rates in their major processes. The circulating water (CW) pump system, which locates in the intake structure providing a continuous supply of turbine-condenser cooling water, does rarely have flowmeters due to its pipe size exceeding almost one meter, where profile factors can hardly be determined for these large pipes and high flow rate because of the difficulty of factory tests. Conventional flowmeters such as time-of-flight (TOF) ultrasonic flowmeters are sometimes used but cannot achieve the high accuracy of flow rate measurements for large pipes.

Instead of installing any flowmeters, plant operators usually estimate the flow rates to evaluate the cooling performance of the condenser with the Q-H design curve of the pump. However, this Q-H curve often drifts due to the deterioration of pump itself.

In order to achieve the high accurate flow measurement, the measurement of a flow profile should be required to eliminate a profile factor. We have conducted fields test using an ultrasonic pulse-Doppler flowmetering system to measure the flow profile of CW cooling pump flow for the case of a pipe diameter of 1.7m, where the flow rate was around 270 m^3/min. Instantaneous flow profile is widely fluctuating by almost double of the average velocity due to the turbulence of pipe flow and pulsation of CW discharge. Next step of the application of the ultrasonic pulse-Doppler system is to measure the flow rate of nuclear feed water system, with a temperature of 220 degrees C and the pressure of 7.5MPa.

1. INTRODUCTION

Integration of instantaneously-determined flow velocity-profiles, obtained from performing continuous line-measurement over piping is considered to provide an accurate flow rate measurement system as an advanced flowmeter, superior to the conventional flowmeter using a profile factor. The conventional one based on the TOF method depends largely on the accuracy of a profile factor 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. (**Takeda Y**., 1987, 1995).

Meanwhile, the feedwater and CW cooling systems of a power plant are generally exposed to high temperature and/or pressure condition(s) with large pipes. Therefore,

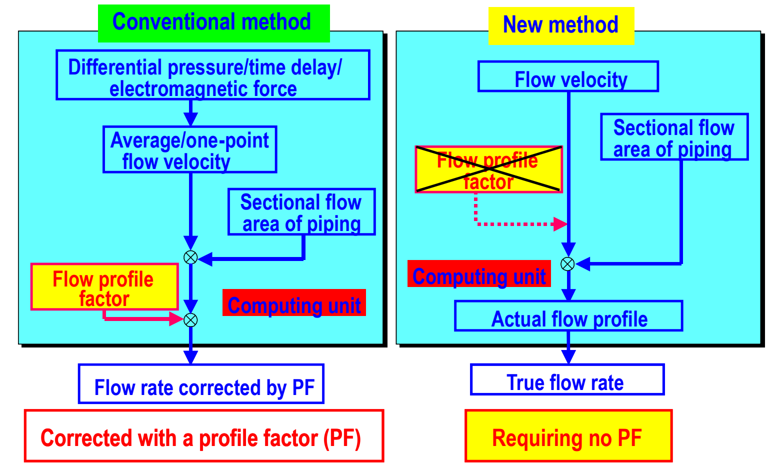

Figure 1. Conceptual Comparison between Conventional Flowmeter and Ultrasonic-Doppler Flow Velocity-Profile Flowmeter.

determining a profile factor under the same flow conditions and the configurations like large pipe diameters and curve bends is impracticable and results in certain errors in measurement. In fact, it is impossible at the present stage to determine a profile factor by a high-precision calibration loop using a weighing method under such high temperature and pressure conditions as in the feedwater or large-bore piping as in the CW cooling system for a nuclear or a fossil-fired power plants. Consequently, the profile factor has to be determined with a Reynolds number approximately one digit smaller than that of the actual plant. In the case of the CW system with a piping bore of ~3 meters for instance, a profile factor determined with the piping bore set at a fraction of the actual size is applied to the system because of constraints from the calibration facilities. The conventional ultrasonic flowmeters as described above round off all indeterminate errors by a profile factor as shown in Figure 1. To get rid of these errors, efforts are needed to eliminate the profile factor by determining flow rates based on the calculation of true flow profile in the piping. This concept is described in Figure 1. (**Takeda Y.**, 1998, **Mori M.**, et al., 1999, 2002)

2. APPLICATIONS FOR INDUSTRIAL POWER PLANT

In electric power plants, thousands of flowmeters are installed to measure the flow rates in major processes. Example of Applications of flowmetering systems for Boiling Water Reactor (BWR) is shown in Figure 2, in which, except for the main-steam flow rate, W_{ms}, to a turbine system, the feedwater flow rate, W_{fw}, condenser flow rate, W_{c}, CW cooling pump flow rate, W_{wc}, are water flows. The feedwater flow rate is significant since it affects the regulated thermal output power. The temperature of feedwater is ~220 degrees-C and the pressure is ~7.5MPa, where Reynolds Number is more than 20,000,000. These conditions hardly realize in the weighing method for calibration to determine PFs. The CW cooling flow rate is necessary to evaluate the plant efficiency; however, flowmeters are rarely found in the CW line because of its difficulty to measure the flow rates and pipe sizes beyond one meters.

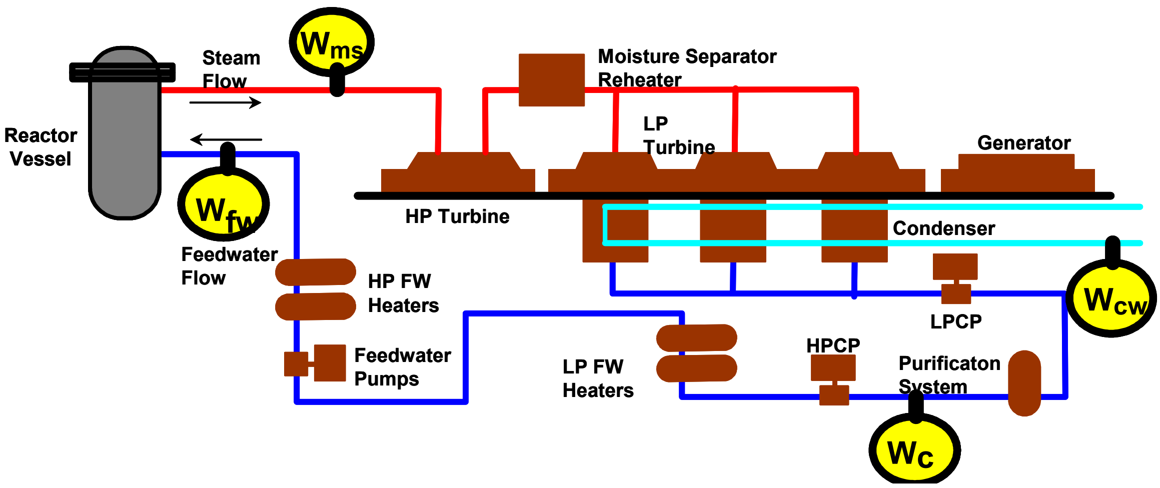

Figure 2. Example of Applications of flowmetering system for Boiling Water Reactor.

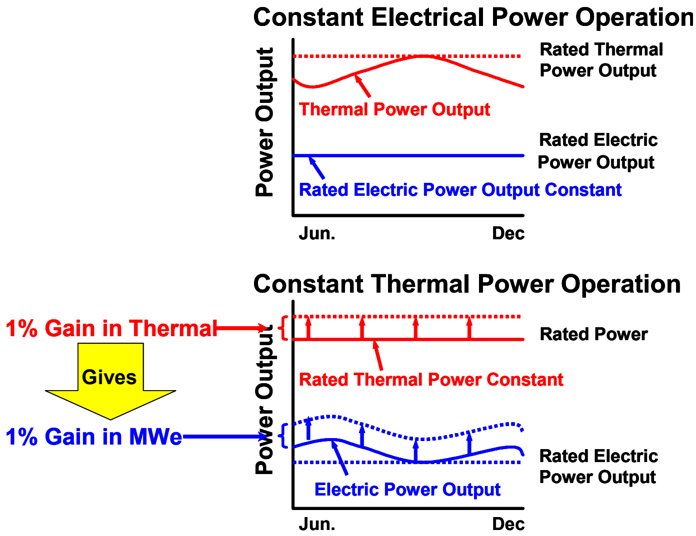

Figure 3. Effects of constant thermal power operation on gained electricity compared with constant electrical power operation.

Figure 3 shows effects of constant thermal power operation on gained electricity compared with constant electrical power operation. Under the constant electrical power operation, the rated electric power output is regulated as constant; on the contrary, the electric output power depends on the effectiveness of the CW cooling system by seawater temperatures in the case of the constant thermal power operation. In the latter case, any gain in thermal power provides certain gain of electricity. However, the thermal power output of a nuclear power plant is strictly regulated, which surely requires an accurate measurement of feedwater flow rates. Aged flow nozzles are considered to indicate higher values than real ones due to its deterioration and erosion. As shown in the following equation, the reactor thermal power output, Q, is significantly affected by the flow rate of feedwater, W_{fw}, the fact of which shows that it is absolutely necessary for the accurate measurement of feedwater to increase the plant availability.

$$W_S \times h_s = (Q - Q_{loss}) + W_{fw} \times h_{fw} + W_{cr} \times h_{cr} - W_{cu} \times (h_{cui} - h_{cuo}) + W_{rec} \times \Delta h_{pump}$$

Q	=	**Reactor Thermal Power**
W_S	=	**Flow Rate of Main Steam**
W_{fw}	=	**Flow Rate of Feedwater**
W_{cr}	=	**Flow Rate of Control Rod Drive System**
W_{cu}	=	**Flow Rate of Reactor Water Clean-up System**
W_{rec}	=	**Flow Rate of Recirculation System**
h_s	=	**Enthalpy of Steam**
h_{fw}	=	**Enthalpy of Feedwater**
h_{cr}	=	**Enthalpy of Control Rod Drive System**
h_{cui}	=	**Enthalpy of Reactor Water Clean-up System Inlet**
h_{cuo}	=	**Enthalpy of Reactor Water Clean-up System Outlet**
h_{pump}	=	**Recirculation Pump Heating**
Q_{loss}	=	**Heat Loss**

3. CALIBRATION TESTS

Measuring tests were conducted at the National Institute of Standard Technology (NIST), a unit under the U.S. Department of Commerce. The flow rate of water per unit length of time can be determined by accumulating in the tank the fluid flowing down the test section in a given period of time and dividing the volume of the fluid thus accumulated by the time elapsed. The nominal measurement error is 0.12%. In this test, the flow of water was measured at the part where it reached the stage of full development. The proposed ultrasonic-Doppler flow velocity-profile flowmeter was found to meet the approved values of the standard loop with an error well within 1%, proving to have sufficient accuracy. Table 1 compares the approved values of the NIST standard loop and corresponding data on the ultrasonic-Doppler flow velocity-profile flowmeter at Re = 400,000. The values of the NIST 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. As indicated in the table, the measuring test found a deviation of only 0.03% between the two devices in terms of the average of the values recorded by five rounds of measurement. From the results of measurement conducted with Re number varied, it was found that the overall average deviation between the two devices was no more than 0.2%. (**Takeda**, 2000; **Mori**, 2002)

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

NIST - U.S. National Institute of Standards & Technology

Run No.	UdFlow	NIST	Deviation L/s	Deviation %
#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%**

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

NMi-J - Japan National Institute of Advanced Industrial Science and Technology

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	Ratio of Flowrate and Uncertainty: Expanded Uncertainty (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%

Further calibration tests were conducted on the ultrasonic-Doppler flow velocity-profile flowmeter by a liquid flowmeter calibration facility, a verification loop, at the National Metrology Institute of Japan (NMIJ), suborgan of the National Institute of Advanced Industrial Science and Technology (AIST), an independent governmental corporation, and Nederlands Meetinstituut (NMI). In NMI, the calibration tests were carried out for water and kerosene. The calibration facility (made to the national standard) has the standard uncertainty set at 0.02% of the reference flow rate. The calibration tests on the ultrasonic-Doppler flow velocity-profile flowmeter were carried out with a measuring instrument attached to the 400A piping section of the facility. 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, compared with the reference flow rate set as a target. Based on the measuring test, the ultrasonic-Doppler flow velocity-profile flowmeter was given a calibration certificate showing an uncertainty range of 0.1% to ~0.5% for water.

Table 3. Comparison of 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

4. FIELD APPLICATION EXPERIMENTS

The field tests were carried out to extend the applicability of the ultrasonic-Doppler flow velocity-profile flowmeter. Table 4 shows the field application experiences of Ultrasonic-Doppler flow velocity-profile flowmeter. The flow rates of the condenser circulation water (CW) were successfully measured for the pipe sizes of 1.5m and 1.7m, where the sufficient ultrasonic reflectors existed in the flow of the pipes to measure the velocity profiles because of low system pressure. The following all cases in Table 4 were measured with a clamp-on type ultrasonic-Doppler flow velocity-profile flowmeter.

Figure 4 shows the measurement result of fields test using an ultrasonic pulse-Doppler flowmetering system for CW cooling flow for the case of a pipe diameter of 1.7m. The time-averaged flow velocity-profile of large pipe with D=1.7m well predicted the parabolic flow profile. Integrating the flow velocity-profile by half over the pipe section provides the flow rate. Figure 5 shows the instantaneous flow profile widely fluctuating by almost double of the average velocity due to the turbulence of pipe flow and pulsation of CW discharge. The parabolic flow profile shown in Figure 4 comes from averaging the instantaneous flow profiles widely fluctuating by almost double of the average velocity. These information could be blind for conventional TOF ultrasonic flowmeters.

Table 4. Field application experiences of Ultrasonic-Doppler flow velocity-profile flowmeter.

System	Pipe Size (m)	Wall Thickness (mm)	Wall Material	Fluid Type	Flow Rate (m^3/min)	Results
Feedwater Pump Bearing Seal Water	0.1	6	Carbon Steel	Condensate Water	0.5	Succeeded
Turbine EHC	0.05	4	Stainless Steel	Mineral Oil	0.01	Succeeded
Plant Discharge Water	0.1	6	Carbon Steel	Water	0.5	Succeeded
Condenser Circulation Water	1.5	14	Carbon Steel	Seawater	450	Succeeded
Condenser Circulation Water	1.7	14	Carbon Steel	Seawater	520	- Succeeded - Bubbles Injected
Hydro Turbine	3.8	12	Carbon Steel	Water	2400	- On-going
Reactor Feedwater Pump Discharge	0.36	28	Carbon Steel	Condensate Water	800	- On-going

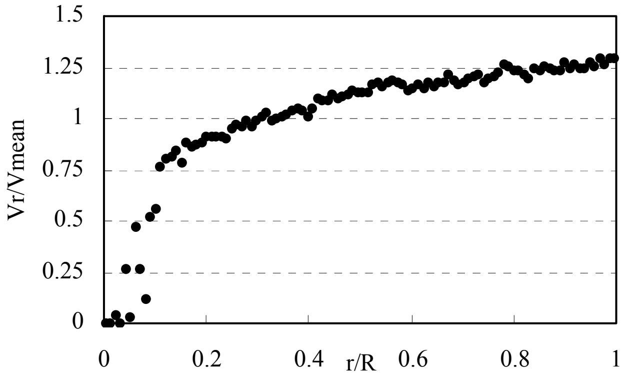

Fig.4 Time-averaged flow profile of large pipe D=1.7m

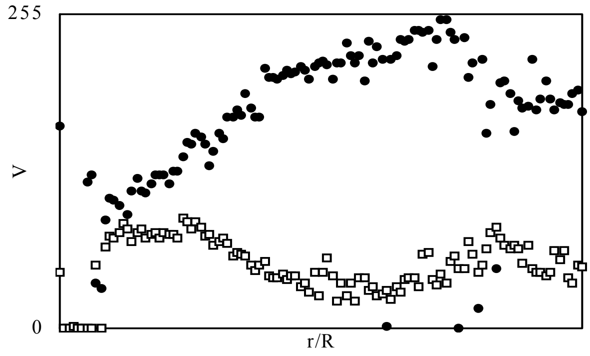

Fig.5 Instantaneous flow profile of large pipe D=1.7m

5. REMARKABLE SUMMARY

The ultrasonic-Doppler flow velocity-profile flowmeter proposed is a new device which, unlike the conventional flowmeters, theoretically dispenses with a profile factor (i.e., adjusting factor) and is capable of accurately measuring true values at the work site of a plant without using some arbitrary adjusting factors. Field applications using the ultrasonic-Doppler flow velocity-profile flowmeter were tested in the various flow and pipe conditions. It is expected that the ultrasonic-Doppler flow velocity-profile flowmeter, with these advantages, will be applied to on-site measurement of true flow rates in large-bore pipes or the calibration of existing flowmeters and pumps installed in pipelines, thereby contributing to the improvement of plants and equipment in efficiency and to the reduction of their maintenance costs.

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