INDUSTRIAL APPLICATION EXPERIENCES OF NEW TYPE FLOW-METERING SYSTEM BASED ON ULTRASONIC-DOPPLER FLOW VELOCITY-PROFILE MEASUREMENT

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ABSTRACT

Velocity-profile measurement by ultrasonic-Doppler method has recently much advanced for fluid flow measurement; however, the actual application is in uncharted territory for high temperature/pressure and high velocity fluid in thick and large industrial piping. The measurement tests of the flow rate using ultrasonic-Doppler flow velocity-profile measurement were carried out at the test loops in NIST (National Institute of Standard and Technology of the United States), NMIJ (National Metrology Institute of Japan), and industrial piping of ~400 mm in diameter. The tests showed errors of ~0.2% for NIST and ~0.4% for NMIJ.

1. INTRODUCTION

A technology to instantaneously determine flow rates by spatially performing continuous line-measurement of flow velocity-profile in piping is considered to provide an advanced ultrasonic flowmeter, superior to the conventional flowmeter using a transit time or time of flight (TOF) method. 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.

Meanwhile, the feedwater and circulating water systems of a power plant are generally exposed to high temperature/pressure conditions or consist of large pipes. Therefore, determining a profile factor under the same flow and shape conditions 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/pressure conditions as in the feedwater or large-bore piping as in the circulating seawater system for a nuclear power plant. 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 a circulating water 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.

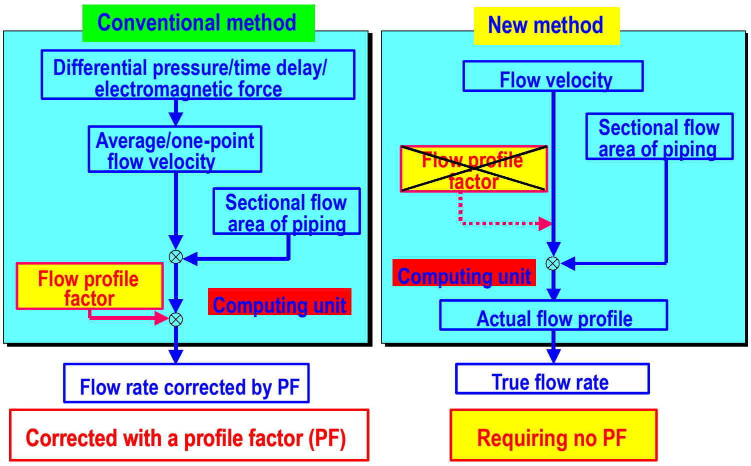

Figure 1. Conceptual Comparison between Conventional Flowmeter and Ultrasonic-Doppler Flow Velocity-Profile Flowmeter.

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. The ultrasonic-Doppler flow velocity-profile flowmeter proposed in this paper can accurately determine the true value of flow at the work site of a plant, not depending on such conditions as the piping bore, temperature and pressure, as far as the basic frequency of ultrasonic waves, Doppler-shift signals, sound velocity and measuring configuration are known. Apparently this capability gives the proposed flowmeter a wide range of industrial applications and advantages in measuring principle and applicability to operational plants over the conventional TOF or one-point ultrasonic-Doppler flowmeter, which involves wider errors whenever the flow velocity-profile or configuration in piping varies.

2. MEASURING PRINCIPLE

The proposed ultrasonic-Doppler flow velocity-profile flowmeter is a method of simultaneously measuring multiple points on the line of flow velocity-profile using a Doppler-shift in ultrasonic pulse echo, and it features capability of instantaneously obtaining spatial information(**Takeda**, 1987, 1995). Figure 2 shows a concept of its measuring principle. The new flowmeter calculates flow velocity-profile by processing signals on the line of measurement based on Doppler signals of an ultrasonic wave that is transmitted from ultrasonic transducers installed on the piping and reflected from bubbles, etc. in the fluid to be measured. This method, with the same meaning as the process of solving Navier-Stokes equation, is capable of determining flow rates more accurately than previous methods and expected to have a wide area of applications. The flow of a fluid even in round piping with a circular cross section would have unsteady-state three-dimensional distribution wherever it is not provided with a sufficient entrance-run length or it is affected by such temporal fluctuations as valve opening and closing or pump startups and stops. In a strict sense, therefore, a three-dimensional map should be prepared by a time-dependent process to determine the flow in the piping under these conditions. In this process, the flow can be determined by the following equation (**Takeda**, et.al. 1998):

$$Q(t) = \int V(t)ds = \iint V_x(r,\theta,t)rdrd\theta$$

Where *Vx* denotes an axial component of the flow on the cross section of the piping. Assuming that the flow is of approximately one dimension, given

$$V_x >> V_r \approx V_\theta$$

the flowmeter can be simplified as follows:

$$Q(t) = \sum_i^N \{\Delta\theta \int_{-R}^{R} v(r,\theta_i,t) / \sin(\alpha) rdr\} \qquad ;\Delta\theta = 2\pi / N$$

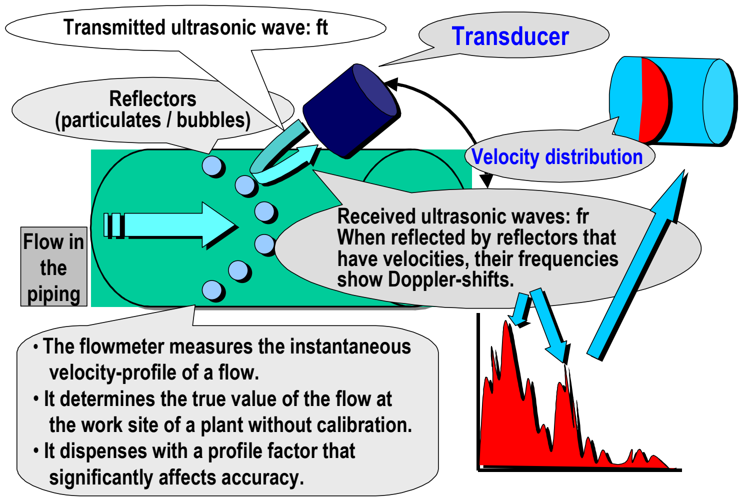

Figure 2. Measuring Principle of Ultrasonic-Doppler Flow Velocity-Profile Flowmeter

In this instance, N units of transducers are installed at the same place on the pipe wall with their circumferential angle varied, but only one line of measurement is sufficient to determine the flow in a passage of piping with stable flow profile. The lines of measurement should be inclined at a certain angle with a perpendicular to the pipe wall and arranged in such a way that all of them will cross the pipe axis.

3. ADVANTAGES OVER CONVENTIONAL FLOW MEASUREMENTS

The conventional measuring methods which also use ultrasonic waves could not accurately measure flow rates if postulated conditions of calibration, such as fully-developed flow profile and conditions, are disturbed because these methods determine flows using flow velocity at one point on the pipe axis or average flow velocity on the pipe diameter. Meanwhile, the proposed ultrasonic-Doppler flow velocity-profile flowmeter measures the flow velocity of the fluid instead and consequently it has many advantages for industrial applications, including those mentioned below:

(a) Profile factors for the calibration can be eliminated in the measurement of flow rates in the work site of a plant.

(b) The accurate measurement of flows is enabled for those like a flow not to be fully developed shortly after a bent pipe.

(c) The whole piping filled up with a fluid is not indispensable essentially for the measurement.

(d) It is applicable to opaque fluids and viscous fluids, in which the calibration can be hardly performed to measure a flow rate, to mention a few of its other advantages.

(e) In addition, as common in ultrasonic flowmeters, the measurement does not disturb the flow in the piping, as it is generally capable of noncontact measurement.

4. CURRENT STATE OF DEVELOPMENT

The development of a flow velocity-profile measuring method using ultrasonic-Doppler effect progressed in recent years for the purpose of measuring the flow velocity-profile of fluids in general and it has come to be used in many areas of fluid experiments and measurement. However, its application to the measurement of high-velocity flows in large-bore, thick-wall industrial pipes as those installed at power plants still remains an unknown field.

4.1 Transient Flow Measuring Tests

Up to now, a series of tests has been carried out on the proposed new method in measuring the flow velocity-profile and flow rate of a fluid in steel piping of ~400A class at normal temperature and normal pressure, and the results have been compared with the values

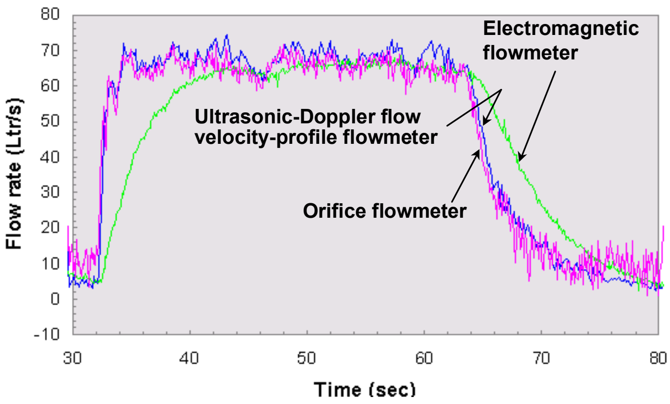

Figure 3. Comparison in Transient Flow Test on Ultrasonic-Doppler Flow Velocity-Profile Flowmeter

measured by a differential-pressure flowmeter and an electromagnetic flowmeter(**Mori**, 1999). An example of the measured results is given in Figure 3. The ultrasonic-Doppler flow velocity-profile flowmeter in these tests achieved desirable results of measurement. As is apparent from the diagram, the conventional differential-pressure method and the ultrasonic-Doppler flow velocity-profile flowmeter showed the same tendency with respect to fluctuations in transient flow, indicating that both of them well responded to fluctuations at a velocity of around 100 msec. The test findings led to the prediction that the proposed method will attain sufficient capability to measure water flows in the piping systems of operational plants, taking into account the arrangement of pipes and measuring conditions in these facilities.

4.2 Verification Test at NIST

Based on the foregoing knowledge and information, a measuring test was conducted at the National Institute of Standard Technology (NIST), a unit under the U.S. Department of Commerce. Figure 4 gives an outline of the loop test section of the reservoir system for standard calibration flow-metering at NIST. A branch line to a tank for volumetric flow measurement is provided on the downstream side of the loop. 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.

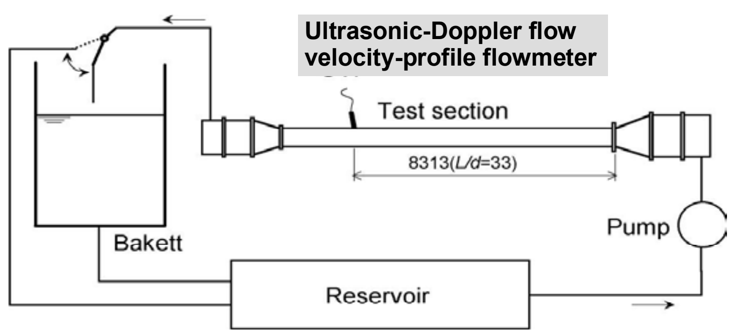

Figure 4. Standard Calibration Volumetric Flowmeter at NIST

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

Table 1. Comparison of Ultrasonic-Doppler Flow Velocity-Profile Flowmeter and Standard Calibration Volumetric Flowmeter at NIST

	UdFlow	*(L/s)*	*NIST Weight*		*Re=400k*	
File	Average	Deviation	GPM	L/s	Difference	% error
N0355.dat	69.760	2.958	1103.30	69.600	-0.161	-0.23%
N0356.dat	69.670	3.191	1103.51	69.613	-0.057	-0.08%
N0357.dat	69.725	3.233	1103.49	69.612	-0.113	-0.16%
N0358.dat	69.444	3.152	1103.65	69.622	0.178	0.26%
N0359.dat	69.569	3.218	1103.44	69.609	0.040	0.06%
Average	69.634	0.128	1103.48	69.611	-0.022	-0.03%

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)

4.3 Calibration Test at National Metrology Institute of Japan (NMIJ)

A calibration test was 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. As shown in Figure 5, the test apparatus flows water from the overflow tank into the measuring pipe for calibration tests and then measures the flow rate of water while sending it by a diverter into the weighing tank installed in the downstream section for a certain length of time. The calibration facility (made to the national standard) has the standard uncertainty set at 0.02% of the reference flow rate. The calibration test on the ultrasonic-Doppler flow velocity-profile flowmeter was carried out with a measuring instrument attached to the 400A piping section of the facility. The results of the test are summarized in Table 2. 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 0.4%.

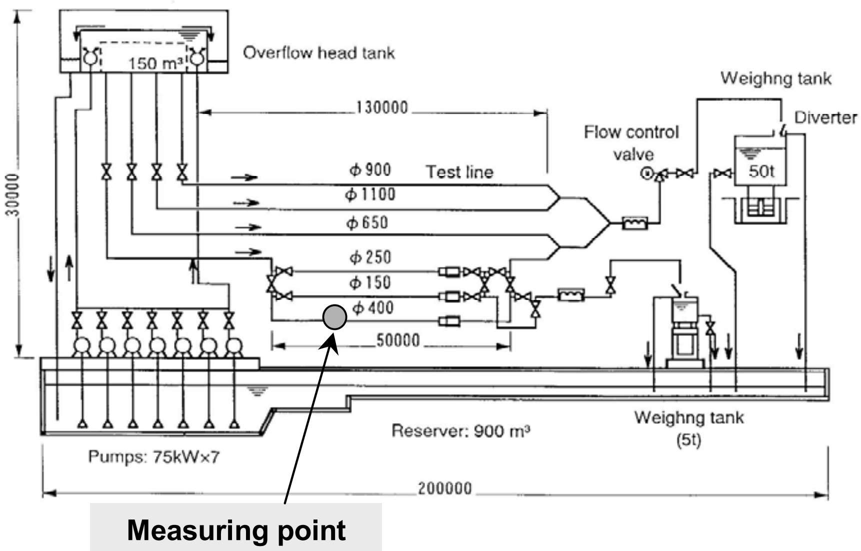

Figure 5. Liquid Flowmeter Calibration Facility at the National Metrology Institute of Japan of AIST

5. RANGE OF APPLICATION

The ultrasonic-Doppler flow velocity-profile flowmeter is based on a continuous pulse Doppler linear measuring method, in which uniform distribution of ultrasonic wave reflectors is desirable, specifically micro-bubbles, in the fluid to be measured. This means that the proposed new flowmeter has to effectively utilize cavitation bubbles in the flow after the pump outlet as well as micro-impurities contained in the fluid. Accordingly the flowmeter is considered applicable to the measurement of production lines at pulp and food-processing factories but its application to power plants involves arrangements for mixing bubbles or some other reflectors into the fluid prior to the measurement of flow rates because, in general, feedwater and other systems in these facilities are exposed to high pressure and the fluid in their piping is not expected to contain impurities. However, some power plants have hydrogen, oxygen or other chemical substances injected into the fluid for water chemistry purposes and, in some instances, these substances could be used as reflectors for the ultrasonic-Doppler flowmeter. Besides, there are greater prospects for its application to the measurement of flow rates in the cooling seawater circulation and some other plant systems that are expected to contain reflectors.

Table 2. Results of Calibration Test on Ultrasonic-Doppler Flow Velocity-Profile Flowmeter at the National Metrology Institute of Japan (NMIJ) of AIST

Round of test	Measuring equipment	Avg. value in 5 rounds □m^3/h□	Avg. uncertainty in 10 rounds
#1	UdFlow No.1	2008.9	0.4%
	Ref. value for weighing tank	2000.1	
#2	UdFlow No.1	2008.9	
	Ref. value for weighing tank	2000.9	
#3	UdFlow No.1	1508.2	0.□%
	Ref. value for weighing tank	1511.8	
#4	UdFlow No.1	1508.2	
	Ref. value for weighing tank	1513.5	
#5	UdFlow No.1	985.5	0.3%
	Ref. value for weighing tank	986.1	
#6	UdFlow No.1	983.7	
	Ref. value for weighing tank	986.0	

The ultrasonic-Doppler flow velocity-profile flowmeter can determine true values at the work site of a plant because it finds the flow rate of a fluid from flow velocity-profile and, consequently, it dispenses with a profile factor that depends on such flow conditions. Accordingly the proposed new type flowmeter is capable of on-site calibration with true values, which it has been impossible to carry out in the past. This implies that the new flowmeter is very effective in reducing the cost of flow measurement as its introduction will eliminate the need to detach flowmeters or large pumps from plant lines and send them to a measuring facility for calibration.

The following are examples of conceivable applications of the ultrasonic-Doppler flow velocity-profile flowmeter:

(a) Measurement, Calibration, and Monitoring of Flow Rates in Pipes Containing Ultrasonic Wave Reflectors.

Those parts that contain bubbles and cannot be accurately measured by any other flowmeter.

Turbid fluids flow rate in pipes carrying high-viscosity fluids.

Surveillance of leaks in pipelines, etc.

(b) Measurement of Flow Rates in Large-Bore Pipes and On-Site Calibration with True Values.

Measurement of flow rates in cooling seawater circulation systems, etc. (with a piping bore of several meters)

On-site calibration of feedwater flow rates, etc. (with the flow rates measured by supplying reflectors mostly from nozzles for cleaning)

(c) Measurement of Flow Profile

Measurement of flow velocity-profile in containers and pits for the improvement of facilities, design changes, troubleshooting service, etc.

6. CONFIGURATION AND EXTERNAL VIEW OF ULTRASONIC-DOPPLER FLOW VELOCITY-PROFILE FLOWMETER

Figure 6 shows the basic configuration of the ultrasonic-Doppler flow velocity-profile flowmeter. The proposed ultrasonic-Doppler flow velocity-profile flowmeter processes signals from ultrasonic transducers with transmitter-receiver functions attached to the piping. The optimization of ultrasonic transmission frequency and repeating frequency is fully attained by a personal computer that also provides remote-control functions for the main unit of the flowmeter. All results of measurement can be seen on the PC display unit. Figure 7 shows an external view of an experimentally made prototype ultrasonic-Doppler flow velocity-profile flowmeter.

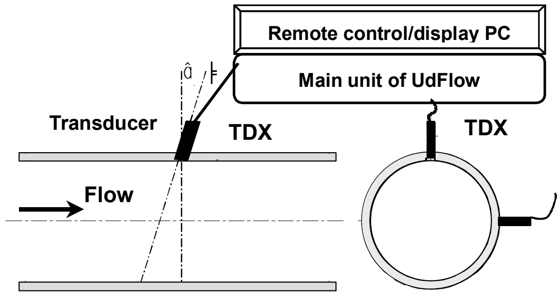

Figure 6. Basic Configuration of Ultrasonic-Doppler Flow Velocity-Profile Flowmeter

Figure 7. Experimentally Made Prototype

One ultrasonic transducer is sufficient to accurately measure flow rates in those parts of piping which carry well-developed flows, as proved by measuring tests at NIST and NMIJ. However, flow rates in the parts which are not far from a bend in the piping or which carry inadequately-developed flows and are subject to disturbance in flow profile have to be measured with two or more ultrasonic transducers properly arranged on one and the same plane. For this purpose, each of the personal computers used for the new flowmeter is provided with capability to respond to signals from three transducers.

Figure 8 gives an example of the ultrasonic-Doppler flow velocity-profile flowmeter measured flow profile shown on a PC display unit. As is apparent from the photograph, the plotted data clearly show the parabolic flow velocity-profile on the diametrical line of the piping.

7. CONCLUDING REMARKS

The ultrasonic-Doppler flow velocity-profile flowmeter proposed in this paper 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. It is expected that the ultrasonic-Doppler flow

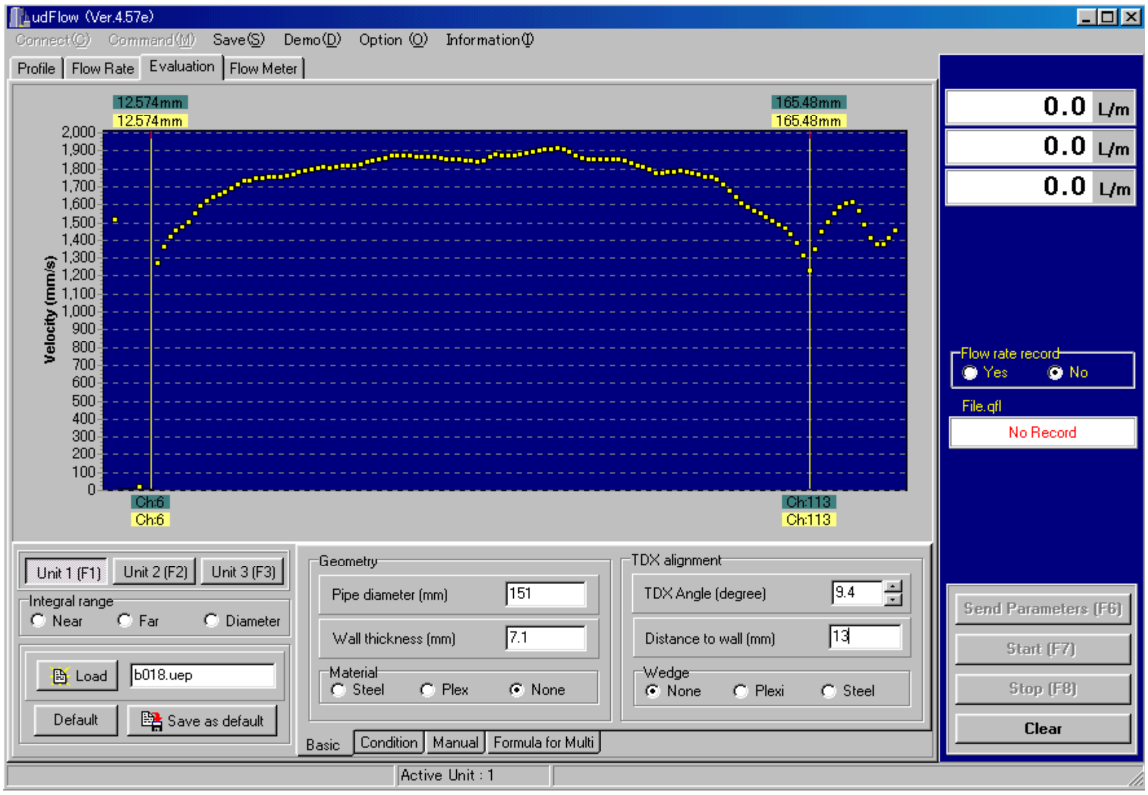

Figure 8. Configuration of Display Unit for Flow Profile Measured in Ultrasonic-Doppler Flow Velocity-Profile Flowmeter, showing the Time-Averaged Flow Velocity-Profile during On-Line Measurement to Compute the Flow Rate by Integrating the Profile.

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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