ADVANCED HYBRID TYPE ULTRASONIC FLOW METER UTILIZING STATE-OF-THE-ART PULSED-DOPPLER METHOD ALONG WITH TRADITIONAL TRANSIT TIME METHOD

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ABSTRACT

This time, new hybrid type ultrasonic flow meter has been developed worldly at first as non-intrusive type one, utilizing UVP (Ultrasonic-Doppler Velocity Profile) method along with transit time method. For its configuration, a pair of clamp-on type ultrasonic transducers is located opposite to each other on a pipe surface. It enables diametric measurement of velocity profiles in case of UVP method, and measurement of time difference in case of transit time method, where these methods would be automatically switched over to each other yielding to conditions of measured liquid and magnitude of velocity. The basic study was done on switchover algorithm, and also the authors have got the prospect of achieving high accuracy (±0.5% of rate) for UVP method by taking measures against various types of acoustic interference and performing actual flow tests.

Keywords: UVP, Transit Time, Hybrid ultrasonic flow meter, Clamp-on, Velocity profile

1. INTRODUCTION

In terms of UVP method, some papers have been reported recently, aimed at industrial flow measurement [1]-[5]. UVP method can measure velocity profiles directly without any correction coefficient which is usually needed for the other flow meters such as ultrasonic transit time meter. Therefore it enables highly accurate flow rate measurement even for undeveloped flow. However, it has to be recognized that there are a few limitations due to its measuring principle. Firstly, to get enough intensity of echo signals with Doppler shift, UVP method requires bubbles and/or particles as tracers of velocity field in measured liquid. Secondly, the measurable maximum velocity is limited to rather a lower value than that of the other flow meters due to the sampling theorem. For example, the maximum velocity is 10 m/s for EMF (electromagnetic flow meter), but it is limited to less than 10 m/s for UVP method. Thirdly, when applying it to non-invasive flow metering, diametric measurement of velocity profiles cannot be done due to acoustic noises nearby ultrasonic transducer, and this time it was confirmed that velocity profiles are affected by various types of acoustic noises, especially for metal pipes.

On the other hand, transit time method has been commonly adopted for industrial non-invasive ultrasonic flow meter so far. In general, it is adequate for clean liquids such as ultra pure water in semiconductor use because it utilizes penetration of ultrasonic waves in liquid. There will be no limit for the maximum velocity without aeration. However, this method has some limitations as well. Firstly, it needs a conversion factor of average velocity with the assumption of fully developed flow. Secondly, although transit time method has been improved for aeration problems by utilizing digital signal processing technology, it is not so tough enough as to be applicable to all kinds of bubbly and/or opaque liquids.

Both methods have strong and weak points as above, but they have complementary roles to each other. New hybrid type ultrasonic flow meter has been developed as non-invasive type flow meter, utilizing UVP method along with transit time method. For its configuration, a pair of clamp-on type ultrasonic transducers is located opposite to each other on a pipe surface. It enables diametric measurement of velocity profiles in case of UVP method, and measurement of time difference in case of transit time, where these methods would be automatically switched over to each other yielding to conditions of measured liquid and magnitude of velocity.

In this paper, main specifications and configuration of newly developed hybrid type ultrasonic flow meter are reported. Also actual flow test results of UVP method are reported, showing examples of radius/diametric measurement of velocity profiles with clamp-on type ultrasonic transducers located on a few kinds of materials' pipes.

2. NEW HYBRID ULTRASONIC FLOW METER

As industrial ultrasonic flow meters, transit time method and conventional Doppler method, which cannot measure velocity profiles, have been mainly adopted until today. Transit time method is relatively high accuracy (±1 to ±2%), but it is not suitable for liquids that include a lot of bubbles and/or particles. On the other hand, conventional Doppler method is tougher against them than transit time method, but it has poorer accuracy (±3 to ±5%) than transit time method. Ultrasonic flow meter utilizing both methods is called "hybrid type" one in general.

This time, new hybrid type ultrasonic flow meter has been worldly at first developed, utilizing UVP method along with transit time method, and realizing higher accuracy than the above-mentioned traditional one.

The measuring principle of transit time method is that ultrasonic pulses are transmitted and received between a pair of transducers obliquely and alternately, and that bi-directional transit time and the time difference induced by carry effect of fluid motion are measured, calculating flow rate from them on the assumption of fully developed and axis-symmetric flow. The principle formula is given by

$$Q=(\pi D^2/4)(1/K)\{C/(2\sin\theta)\}\{\Delta T/(T_0-\tau)\} \tag{1}$$

where Q: volumetric flow rate, D: inside diameter, K: conversion factor of average velocity, C: sound velocity of measured liquid, θ: incident angle into liquid, ΔT: transit time difference, T_0: transit time when flow is at rest, τ: transit time in pipe wall and transducers' wedge. The K corresponds to correction coefficient on the assumption of fully developed laminar/turbulent flow.

UVP method utilizes so-called pulsed-Doppler effect, assuming that bubbles and/or particles move with the same velocities as measured liquid. Ultrasonic pulses are transmitted into liquid, echo signals scattered by them are received by the same transducer, the propagation line is divided into small channels, velocity profiles are obtained by connecting Doppler shifts in the channels, and flow rate is calculated by integrating the velocity profiles. The principle formulas are given by

$$Q=\iint v(x)dS \tag{2}$$

$$v(x)=\{C/(2\sin\theta)\}\{f_d(x)/f_0\} \tag{3}$$

$$x=(Ct)/2 \tag{4}$$

where v(x): velocity at position x, $f_d(x)$: Doppler shift at position x, f_0: basic excitation frequency, t: round transit time between transducer and position x, others: ditto.

The main specifications of newly developed hybrid type ultrasonic flow meter are shown in table-1

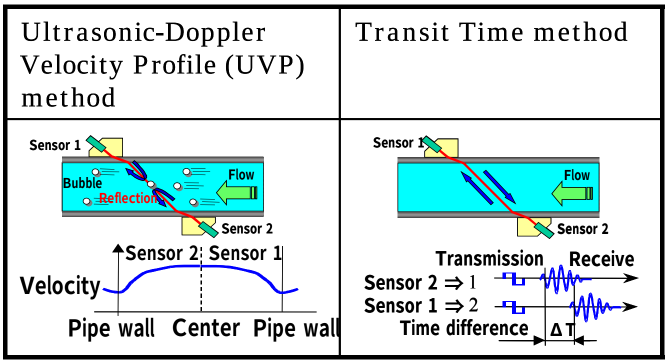

Fig-1: Measuring Principle

		UVP METHOD	TRANSIT TIME METHOD
FUNCTIONS	Installation	Clamp-on	
	Number of path	2 or 4 paths	1 or 2 paths
	Applicable pipe size	φ25 to 1000mm	φ13 to 6000mm
	Pipe material	Metals with / without liner, Plastics	
	Velocity	0 to ±0.3 ---- 4 m/s (depending on dia.)	0 to ±0.3 ---- 32 m/s
	Fluid temperature	- 40 to +100 degC	
	Output	DC4 to 20mA (load 1 kΩ) DO: 3 points RS-232C / RS-485	
	Explosion-proof	ATEX EEx mⅡ T6	
PERFORMANCE	Accuracy	±0.5% of rate	±1% of rate
	Straight pipe length	5D(Up), 2D(Down)	10D(Up), 5D(Down)
	Response time	0.1 s	0.5 s
	Permissible air	0.02 to 20 vol.%	0 to 12vol.%
	Undeveloped flow	Applicable	NA

Table-1: Specifications of New Hybrid Ultrasonic Flow Meter

3. CONFIGURATION OF THE FLOW METER

3-1. TRANSMITTER

The hardware block diagram of the transmitter is shown in Fig-2. It consists of a measurement board, a control board, a man-machine interface, and a power supply board.

1) Measurement board: Supplying transmission signals with ultrasonic transducers, amplifying received signals, converting them to digital data, and then calculating flow rate by digital signal processing.
2) Control board: Measuring temperature of transducer's wedge, and controlling key input, DC4-20mA, DOs, serial port for RS-485/RS-232C, and LCD.
3) Man-machine interface: Setting parameters, and indicating flow rate and total.
4) Power supply board: Power supply to the other boards.

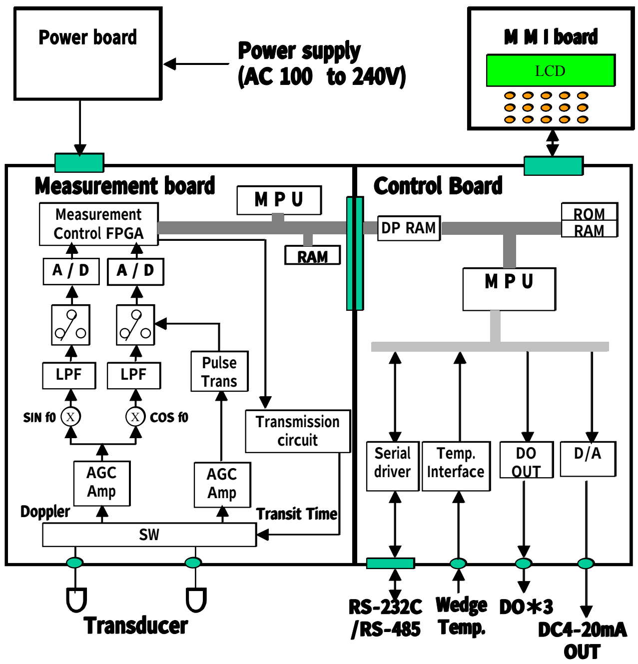

Fig-2: Block diagram of Hybrid Ultrasonic Flow Meter

3-2. DETECTOR

Fig-3 shows the outline of newly developed detector. Composite type piezoelectric oscillator is often used as an ultrasonic transducer for UVP method. However PZT disc is used for the transducers, because the targeting liquid temperature ranges from -40 to +100 deg C, and because of its cost reduction. Optimizing backing structure of PZT disc, Low-Q transducers were made with almost the same efficiency as ones utilizing composite type piezoelectric devices. For highly accurate measurement over wide temperature range, a temperature sensor is incorporated into the transducer's wedge, automatically compensating its sound velocity change. It also enables diametric measurement of velocity profiles by locating a pair of ultrasonic transducers opposite to each other on a pipe surface. This installation makes it possible to use transit time method as well by adjusting the distance between transducers with the same configuration.

Acoustic absorber units are installed just before sensor units, aimed at decreasing the affect of multiple reflection in pipe wall.

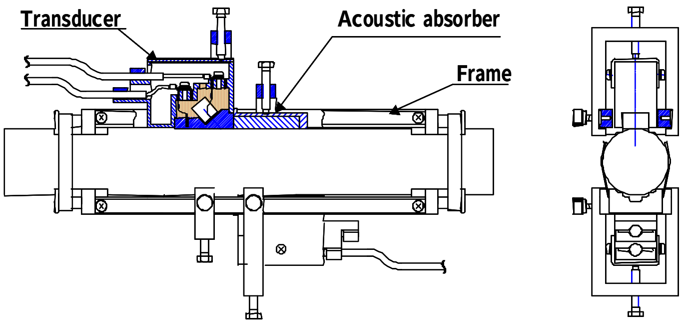

Fig-3: Detector of Hybrid Ultrasonic Flow Meter

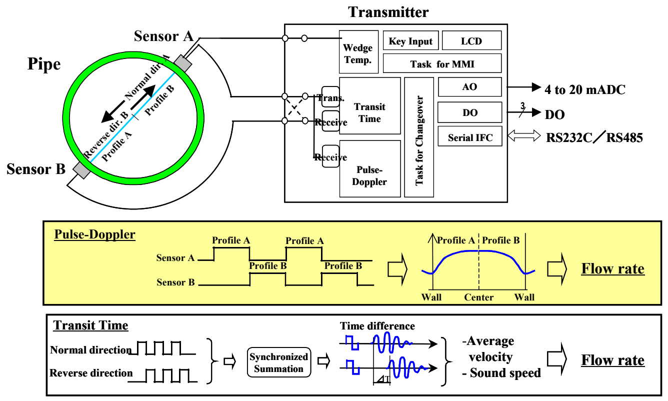

Fig-4: Configuration of Hybrid Ultrasonic Flow Meter

4. SWITCHOVER ALGORIZM

The configuration of hybrid type ultrasonic flow meter is shown in Fig-4, making it possible to use both of UVP method and transit time method. When echo signals are weak due to insufficient existence of reflectors in measured liquid, or when flow velocity exceeds UVP measurable range, transit time method is used. On the contrary, when reflectors increase and then transit time method cannot measure, UVP method is used.

The switchover algorithm is shown in Fig-5. After setting parameters such as pipe material, pipe diameter, wall thickness, kind of liquid, flow range, etc., the maximum velocity will be calculated and checked if it is within UVP measurable range. If the velocity is within the range, the task for UVP method will be performed. And if success rate, which is defined as number of normal channels divided by total channels, is more than for example 70%, it will recover the failed channels, and output and display flow rate. Without UVP measurable range, or if the success rate is less than 70%, the measuring method will be switched over to transit time method. If neither UVP method nor transit time method can measure normally, it will perform a task for alarm output and display.

In case that conditions of measured liquid change, especially the kind of liquid changes time after time, this switchover function of measuring methods makes it applicable to various kinds of liquids and wider applications than now.

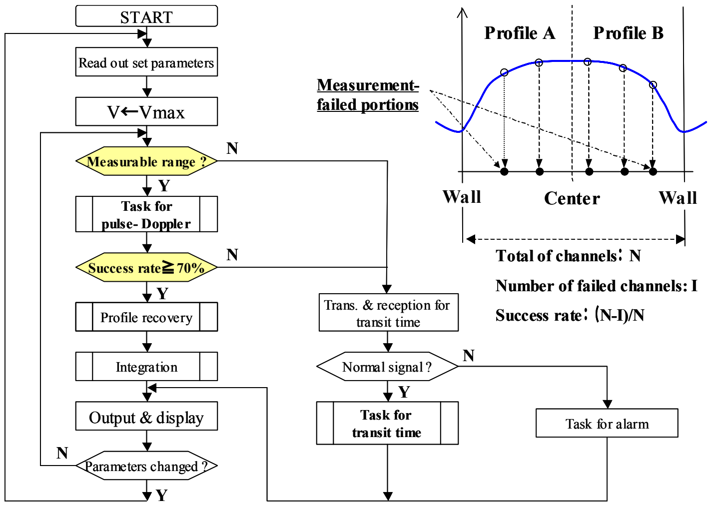

Fig-5: Switchover Algorithm

5. RESULTS OF ACCURACY TESTS

By using the transmitter and the detector, the tests were performed for accuracy evaluation. The tests were done for three kinds of materials, SS (stainless steel), PVC and CS (carbon steel) with ca. 100 mm. The test loop is shown in Fig-6. A flow conditioner, so-called Akashi type, was installed on the upstream side of the pipe. The detector that consists of one transducer only was installed on the pipe surface by 7D downstream from the flow conditioner. The tests were performed by so-called comparison method, where an EMF installed on downstream side was used as the reference meter. The EMF was calibrated within 0.1% by gravimetric method. The liquid was water that contains air bubbles as velocity field tracers. Air was injected into water on the suction side of upstream pump, and broken into small air bubbles by the pump. The mixture ratio was set to ca. 0.02 to 0.2 % in volume owing to flow rate. The excitation frequencies were set to specific values to make the effect of dispersion due to finite pipe thickness at the minimum.

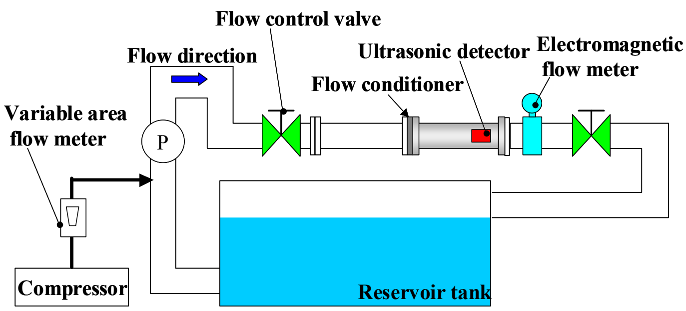

Fig-6: Test Facility for Accuracy Evaluation

The actual flow tests were done at the average velocities from 0.2 to 2 m/sec. The test results are shown in Fig-7 to 9. The examples of velocity profiles at the time of these tests are shown in Fig-10 to 12. For the range of more than 0.4 m/sec, they are within nearly ±1%. For the range of more than 1 m/sec, they are within nearly ±0.5%. It has been confirmed that almost the same accuracy as EMF can be realized.

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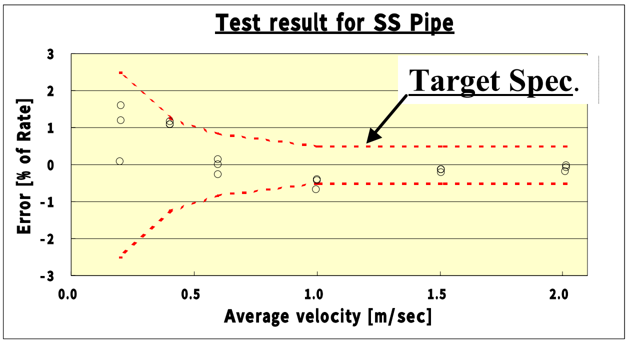

Fig-7: Accuracy Evaluation for SS Pipe
Inside diameter: 102.2mm,
Wall thickness: 5.9mm
Integral range: Far radius

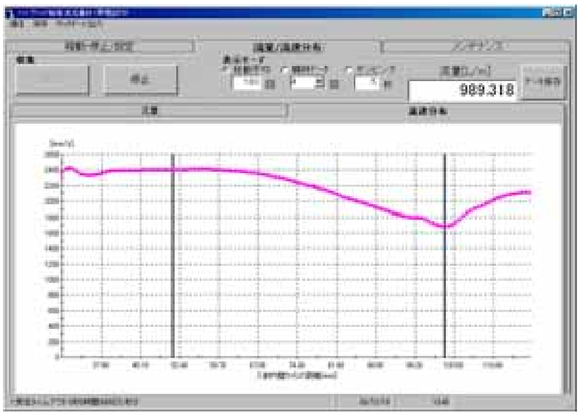

Fig-10：Radius Velocity Profile for SS Pipe (2 m/sec)

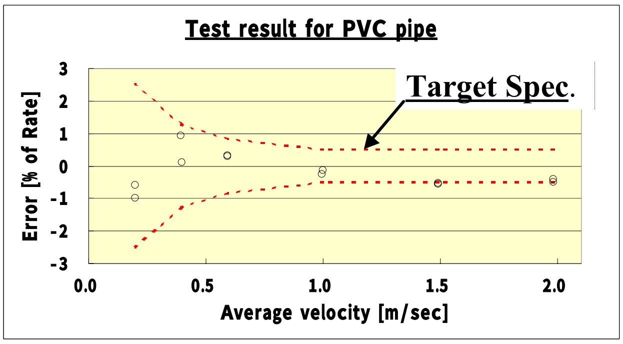

Fig-8: Accuracy Evaluation for PVC Pipe
Inside diameter: 104.2mm
Wall thickness: 4.8mm
Integral range: Far radius

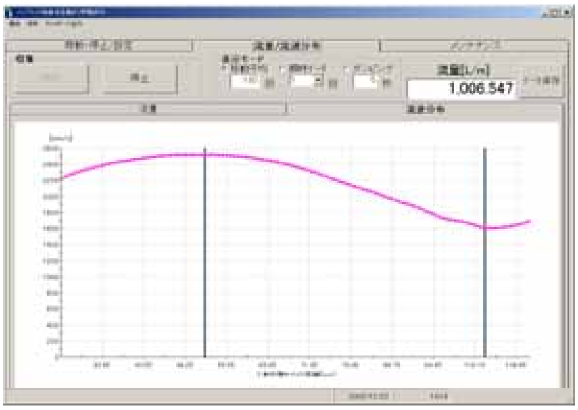

Fig-11: Radius Velocity Profile for PVC Pipe (2m/sec)

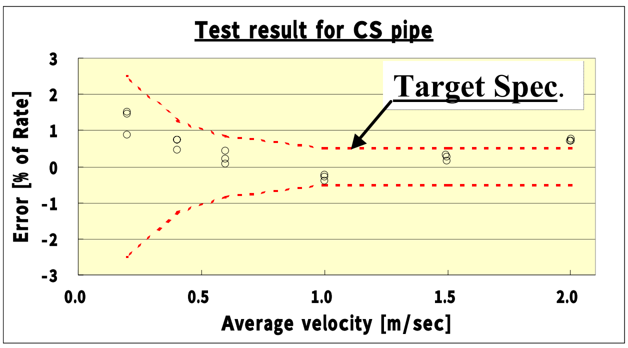

Fig-9: Accuracy Evaluation for CS Pipe
Inside diameter: 106.0mm
Wall thickness: 4.3mm
Integral range: Far radius

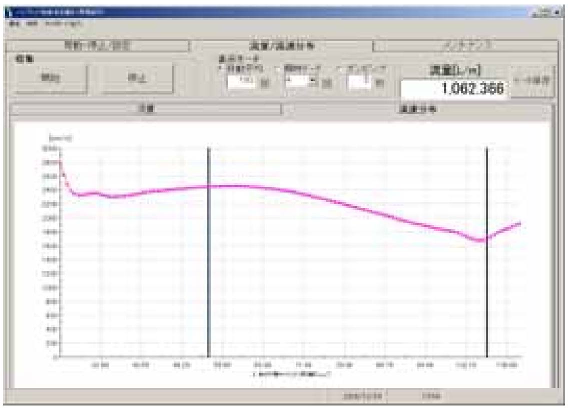

Fig-12: Radius Velocity Profile for SS Pipe (2m/sec)

Next, as shown in Fig-3 and 4, with a pair of transducers installed opposite to each other, accuracy evaluation was performed. The test result is shown in Fig-13. The velocity profiles are shown in Fig-14 and 15 at that time. It was confirmed that two radius flow profiles coincide to each other in the central regions

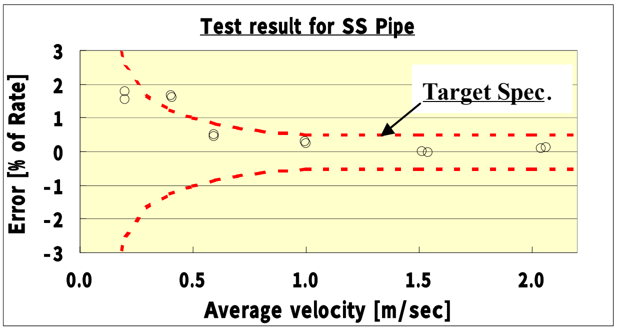

Fig-13: Accuracy Evaluation for SS Pipe
Inside diameter: 102.2mm
Wall thickness: 5.9mm
Integral range: Diameter

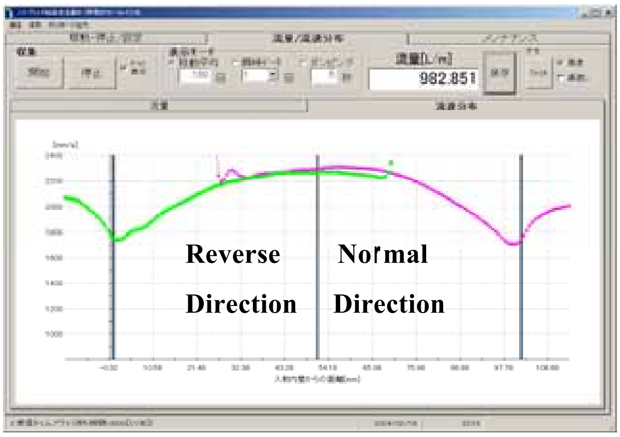

Fig-14: Diametric Velocity Profile for SS Pipe (2 m/s)

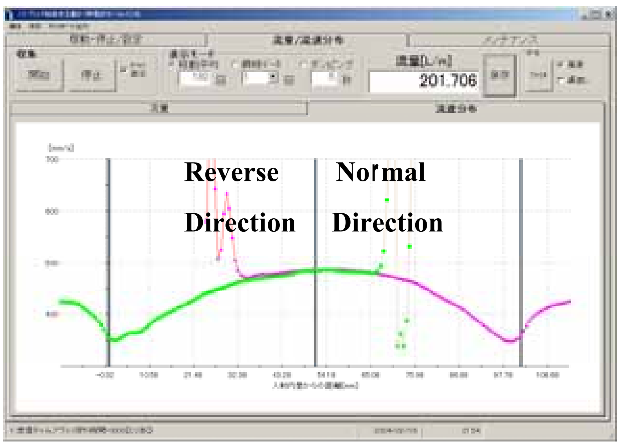

Fig-15: Diametric Velocity Profile for SS Pipe (0.4 m/s)

6. CONCLUSIONS

This time, new hybrid ultrasonic flow meter has been developed, combining UVP method with transit time method. And actual flow tests were performed by using clamp-on detector for three kinds of materials' pipes with diameter of ca. 100 mm. The accuracy was within ±0.5 to ±1.0 % of rate, therefore the authors have got the perspective to be able to achieve the accuracy equivalent to EMF. In addition, it was confirmed that diametric flow profiles can be obtained in real time with a pair of transducers installed opposite to each other on a pipe surface.

In addition, the changeover algorism between UVP method and transit time method was studied.

7. REFERENCES

1. Y. Takeda, Velocity profile measurement by ultrasound Doppler shift method, Int. J. HEAT & Fluid Flow, Vol.17, No.4, pp.313-318 (1986)
2. M. Mori, Y. Takeda, T. Taishi, N. Furuichi, M. Aritomi, H. Kikura, Development of a novel flow metering system using ultrasonic velocity profile measurement, Exp. Fluids, 32, pp.153-160 (2002).
3. K. Tezuka, H. Tezuka, M. Mori, Y. Takeda, H. Kikura, M. Aritomi, N. Furuichi, Development of flow rate and profile measurement using ultrasonic Doppler method (17) Effects of pipe elbows on swirl and Reynolds number changers, Atomic Energy Society of Japan's autumn annual conference in 2003, pp.396
4. S. Wada, H. Kikura, M. Aritomi, Y. Takeda, M. Mori, Development of flow rate and profile measurement using ultrasonic Doppler method (18) Multiline flow rate measurement on inlet flow after pipe elbow, Atomic Energy Society of Japan's autumn annual conference in 2003, pp.397
5. K. Tezuka, H. Tezuka, M. Mori, Application of Ultrasonic Pulse-Doppler Velocity-Profile Flowmeter for Large Pipings, pp.34 (2003)