A Multi-Path Ultrasonic Transit Time Flow Meter Using a Tomography Method for Gas Flow Velocity Profile Measurement

Deddy Kurniadi, Amoranto Trisnobudi*

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Abstract

A velocity profile is the distribution of velocities in the axial direction over a cross-section of circular pipe. In this study, a new ultrasonic flow meter with a modified multi-path configuration, namely, a tomographic ultrasonic flow meter is proposed for the measurement of the flow velocity profile. The flow meter consists of a set of transmitting transducers and a set of receiving transducers placed at different positions on the pipe surroundings. This configuration produces an ultrasonic path in various directions and positions for the flow detection. Transmitting transducers, in sequence, propagate the ultrasound wave to all receiving transducers, and the axial velocity in each ultrasonic path is measured. The average velocity is calculated by using the weighting method. Using the theoretical flow profiles, the tomographic ultrasonic flow meter is simulated in asymmetric flow and compared to both the diametrical and quadrature configurations. The filtered back projection method is employed to reconstruct a flow velocity profile. In the reconstruction process, the flow velocity obtained in each ultrasonic path is used as the projection data. An experiment is also performed in a circular pipe for measuring the air flow velocity profile, in order to validate the proposed flow meter.

Keywords: flow velocity profile, tomography, transit time ultrasonic flow meter

1 Introduction

Until recently, most industrial flow meters have been designed specifically for measuring average velocity. However, a flow meter that can be used for measuring the flow velocity profile is also required. The velocity profile is defined as the distribution of velocities in the axial direction over the cross-section of a circular pipe. Detailed information about the velocity distribution is very important, e.g., in the oil and gas industries, where the flow velocity distribution might be useful for more accurate calculation of the amount of oil and gas that has been distributed and sold to customers through a certain pipeline.

Nowadays, there are many kinds of flow measuring principles which might be used for velocity profile measurements such as ultrasonic flow metering, magnetic flow metering, etc. [1]. One important type is the multi-path ultrasonic transit time flow meter, which is being intensively studied and developed [2–4]. Such meters are already used for industrial flow velocity profile measurement, either for process monitoring or custody transfer. In practice, there are many configurations of ultrasonic transit time flow meters such as diametrical, mid-radius, orthogonal and quadrature. In general, they consist of a set of transmitter-receiver pairs, where each transmitting transducer propagates the ultrasonic wave to a particular receiving transducer.

The velocity profile depends on the fluid properties and the pipe configuration, which is usually not uniform. This condition will produce an asymmetric flow profile and as a consequence, will affect the accuracy of the measurement. The ultrasonic flow meter with multi-path transducer configuration is designed to obtain more accurate measurement results for either the symmetric or

* D. Kurniadi, A. Trisnobudi, Department of Engineering Physics, Bandung Institute of Technology, Jalan Ganesha 10, Bandung 40132 (Indonesia).
E-mail: kurniadi@tf.itb.ac.id

asymmetric flows. Many researchers have investigated the problem of the accuracy of multi-path ultrasonic flow meters, e.g., Moore et al. [2] have developed a methodology for evaluating the performance of ultrasonic transit time flow meters in some asymmetric flow profiles. They investigated seven different configurations of ultrasonic flow meters with equally weighted measurement paths. The authors used some theoretical flow profiles and three parameters to describe the performance of the flow meter, i.e., hydrodynamic factor, orientation sensitivity factor and orientation range factor. They showed that their methodology is useful for optimizing the design of a multi-path ultrasonic transit time flow meter. In this present study, their methodology will be employed to evaluate the proposed system of the current authors.

This paper describes a new multi-path ultrasonic flow meter for measuring the axial flow velocity profile of gas within a pipe. The proposed flow meter consists of a set of transmitting transducers and a set of receiving transducers placed at different positions on the pipe surroundings. The transmitters are placed in a section of the pipe and the receivers are placed in another section upstream to the position of the transmitters. The flow is electronically scanned by ultrasonic transducers. The ultrasonic waves are propagated in sequence from transmitting transducers and received simultaneously by all receiving transducers. Thus, at any given time, only one transmitter is activated and the propagated wave is received by all receivers. This configuration produces an ultrasonic path in various directions and positions for flow detection. The axial velocity in each ultrasonic path is detected and measured. The total average axial velocity is determined by using the weighting method. The tomography method is employed to estimate the distribution of the axial velocity. In order to evaluate the performance of the proposed flow meter, the hydrodynamic factor and the orientation sensitivity factor are calculated for various asymmetric theoretical flow profiles. Finally, the performance of the proposed flow meter is compared to other ultrasonic flow meter configurations such as the single path flow meter in a diametrical configuration and the four paths flow meter in a quadrature configuration.

The remainder of this paper is arranged as follows: section 2 describes the basic principles used in the present study, i.e., the ultrasonic transit time flow metering and tomography method, and section 3 describes the proposed flow meter and compares it to other ultrasonic flow meter configurations. Section 4 describes the experiments for validation of the concept and the results obtained from the experiments. Finally, section 5 describes the conclusions of the study.

2 Basic Principles

2.1 Ultrasonic Transit Time Flow Meter

The ultrasonic flow meter using the transit time or time of flight method with a single path configuration is depicted in Figure 1. In this flow meter [1], the measurement is performed by transmitting a pulse from a transducer through the fluid to another transducer positioned downstream in the pipe, and back again. The flow velocity is obtained by measuring the difference in the time taken for the signal to travel up and downstream. Therefore, the transit time in the upstream direction t_u, and in the downstream direction t_d, can be expressed by Eqs. (1) and (2), respectively:

$$t_u = \frac{L}{c - V\cos\theta} \tag{1}$$

$$t_d = \frac{L}{c + V\cos\theta} \tag{2}$$

where L is the path length, c is the velocity ultrasound path in the fluid, V is axial velocity measured along the path, and θ is the angle between the sound path and the axial velocity of flow.

From Eqs. (1) and (2), the axial velocity of flow can be calculated as follows:

$$V = \frac{L(t_u - t_d)}{2t_u t_d \cos\theta} \tag{3}$$

In other words, if the ultrasound travel time t^*, is measured in the upstream direction and t_0 is the travel time without flow, then the flow velocity can be expressed as:

$$V = \frac{c(t^* - t_0)}{t^* \cos\theta} \tag{4}$$

In the present system, Eq. (4) is used to calculate the flow velocity.

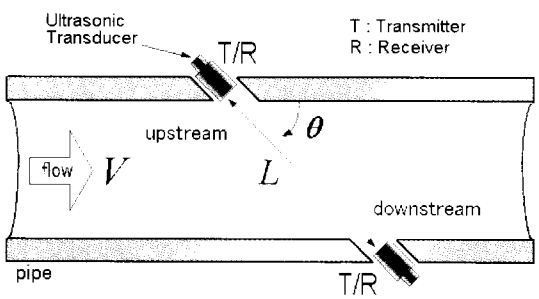


Fig. 1: Single path ultrasonic flow meter.

2.2 Tomography Method

In the present work, a well known reconstruction algorithm from tomography methods, i.e., the filtered back projection is employed [5]. This algorithm is based on the Fourier slice theorem. Consider that $f(x, y)$ represents the characteristic distribution of the object to be studied and $P_\theta(t)$ is defined as its projection function. The function $P_\theta(t)$ is known as the Radon transform of the function $f(x, y)$. If $S(\omega,\theta)$ is the Fourier transform of $P_\theta(t)$, then the Fourier slice theorem is expressed as:

$$S(\omega, \theta) = F(\omega, \theta) = F(\omega\cos\theta, \omega\sin\theta) \tag{5}$$

where $F(\omega,\theta)$ is the 2-dimensional Fourier transform of an object with polar coordinates. The image of the object $f(x, y)$ can be constructed by means of the inverse Fourier transform of $S(\omega,\theta)$. If K is the number of projections, then the reconstructed object function $f(x, y)$ can be written as:

$$f(x, y) = \frac{\pi}{K}\sum_{i=1}^{K} Q_{\theta i}(x\cos\theta_i + y\sin\theta_i) \tag{6}$$

where,

$$Q_{\theta i}(t) = \int_{-\infty}^{\infty} S_{\theta i}(\omega)|\omega|e^{j2\pi\omega t}d\omega \tag{7}$$

Equation (7) represents the filtering operation and Q is known as a filtered projection.

3 Tomographic Ultrasonic Flow Meter

3.1 Transducer Configuration

Based on the principle of transit time ultrasonic flow metering, a new configuration of multi-path ultrasonic flow meter is proposed [6]. The objective of this new configuration is to detect the flow in various directions and positions from many angles. A set of transducers are installed around the pipe in the measurement portion at two cross-sectional planes, i.e., the transmitter and receiver planes. In this work, the flow meter is developed by using 8 transmitting transducers and 8 receiving transducers. The distance between the receiver and transmitter planes is equal to the diameter of the pipe, D. Transmitting transducers are installed in the transmitter plane or downstream plane and receiving transducers in the receiver plane or upstream plane. Each transducer is oriented to maximize the signal amplitude received. The proposed system is called the tomographic (TOMO) ultrasonic flow meter and its configuration is shown in Figure 2.

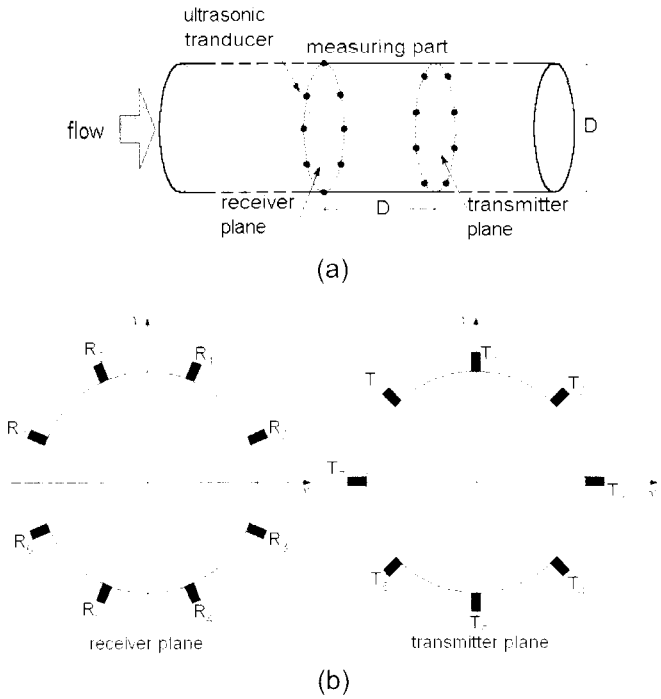
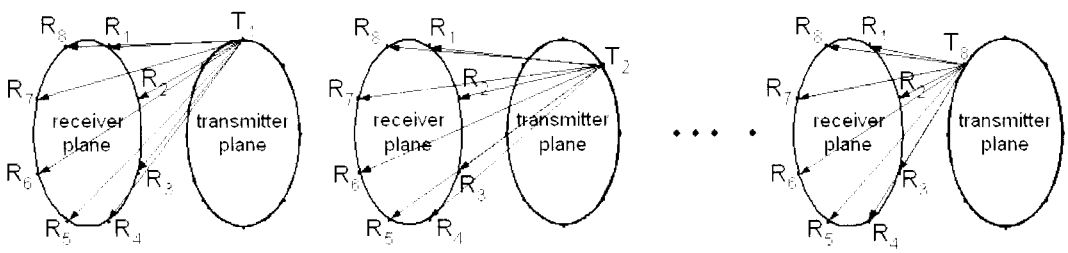


Fig. 2: Transducer arrangement of the tomographic configuration.

The variables being measured are the transit times of the ultrasonic pulse generated only in the upstream direction. The transit time data was collected according to the following procedure, as shown in Figure 3. The transmitter was activated sequentially from the first transmitter to the last transmitter. This procedure is known as scanning of the flow. At any one time, only one transmitting transducer propagates an ultrasonic



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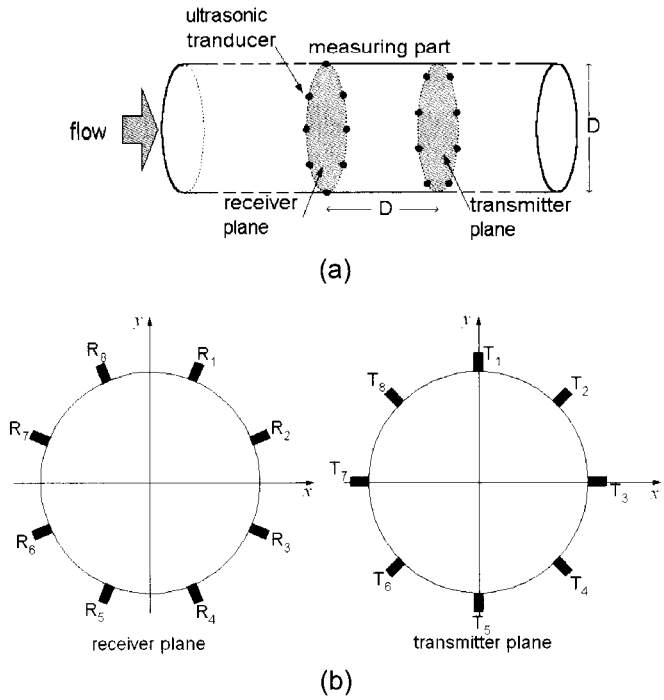

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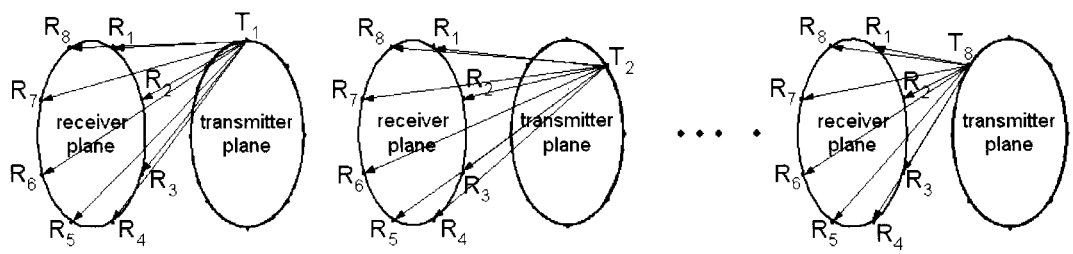

Fig. 3: Data collection procedure.

pulse. In order to obtain a relatively large ultrasonic beam spread angle, the frequency of the transducers should be relatively low. Thus, the ultrasonic beam transmitted from a transmitter can be received simultaneously by all receiving transducers. The total number of the measurement paths is N*N, where N is the number of transmitters or receivers. The measurement path in the data collection process for 8 transmitting transducers and 8 receiving transducers is shown in Figure 4.

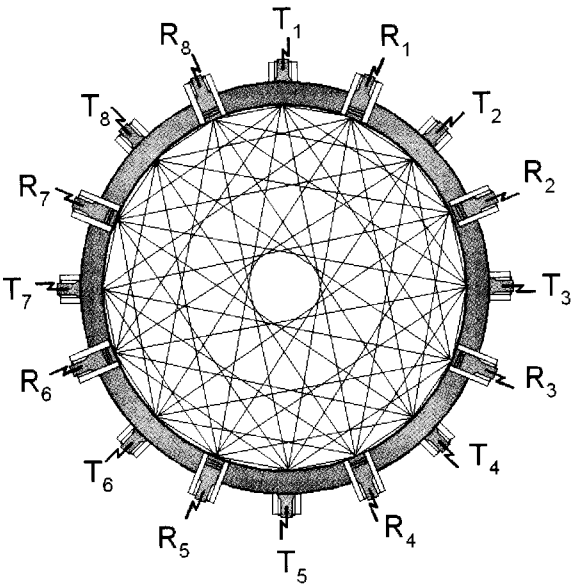

Fig. 4: Transit time measurement path.

After collecting the travel time data in each measurement path, the flow velocity is calculated by using Eq. (4). The different position and orientation of each measurement path will result in different contributions to the total average flow velocity. The weighting method is used for calculating the total average axial flow velocity. The weighting factor w_i, for each path is applied to each velocity and the total average velocity measured is described as:

$$v_{meas} = \sum_{i=1}^{n} w_i (V_{path})_i \tag{8}$$

3.2 Comparison with Other Configurations

To evaluate the performance of the proposed flow meter, two parameters were calculated, i.e., the hydrodynamic factor H, and the orientation sensitivity factor S, to indicate the sensitivity of variation of flow meter configuration to the asymmetric flow. The hydrodynamic factor is defined as the ratio of actual mean velocity in the pipe to that which is measured [2], and it is described by the following equation:

$$H = \frac{v_{act}}{v_{meas}} \tag{9}$$

In the theoretical flow model, the actual velocity is the true mean cross-sectional mathematical function of the velocity, and the measured velocity is the total of all measured velocities along the paths. The orientation sensitivity factor is defined as the range of hydrodynamic factors and described by the following equation:

$$S = H_{\max} - H_{\min} \tag{10}$$

These two parameters are calculated in theoretical flow velocity profiles for the tomographic (TOMO) configuration, and then compared to two other ultrasonic flow meter configurations, i.e., diametrical (DIAM) and quadrature (QUAD). These flow meter configurations are shown in Figure 5. Each flow meter configuration is rotated at increments of 22.5° with respect to the profile for a maximum of 180°.

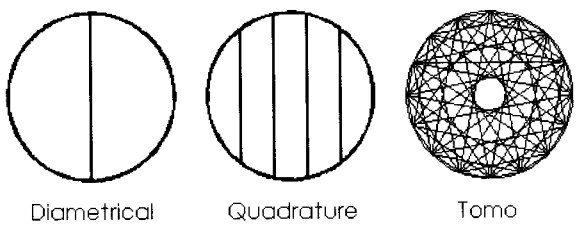

Fig. 5: Three different configurations of ultrasonic flow meter.

The theoretical asymmetric flow velocity profile in a circular pipe of Salami [2] is described by Eq. (11). Moore et al. [2] used this equation in their study to generate 14 profiles. In the present study, only two profiles are used and the parameters are shown in Table 1, with profile 1 having one peak and profile 2 having more complex characteristics. The contour plot of the theoretical flow velocity profiles are depicted in Figure 6.

$$v = (1-r)^{1/n} + mr(1-r)^{1/k} f(\theta) \tag{11}$$

Table 1: Parameters for theoretical flow [1].

Profile	n	k	m	a	$f(\theta)$
1	9	4	$-0.5/\pi$	–	$\theta \sin\theta$
2	9	0.5	-6.7501	0.5	e-a$\theta \sin\theta$

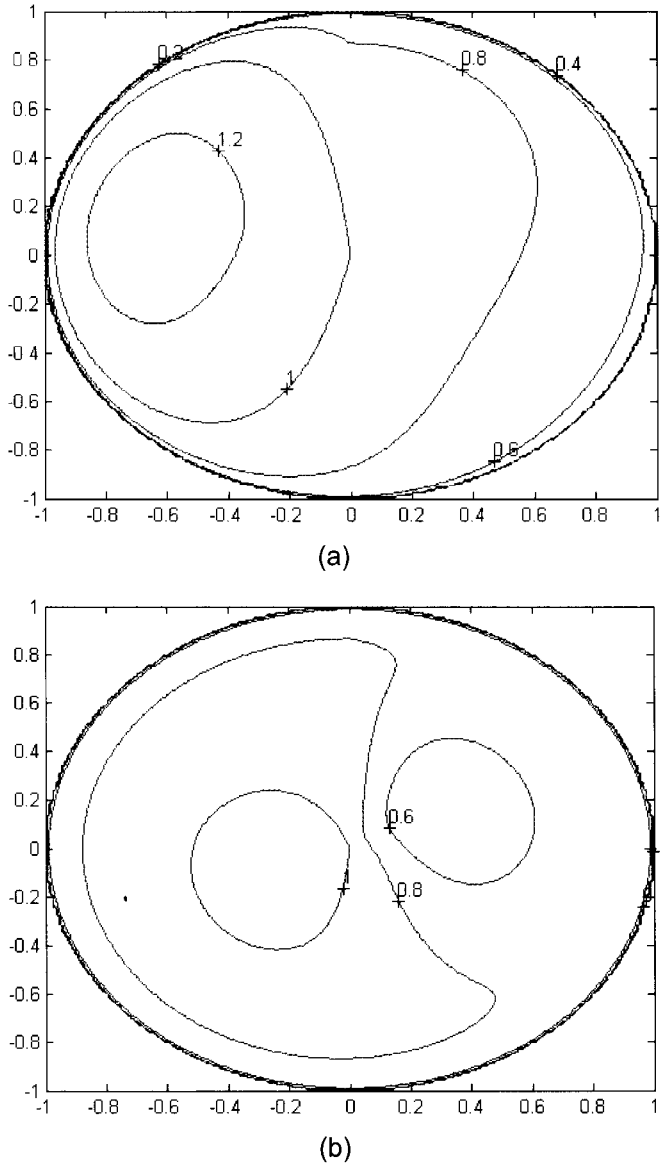

Fig. 6: Theoretical flow velocity profiles.

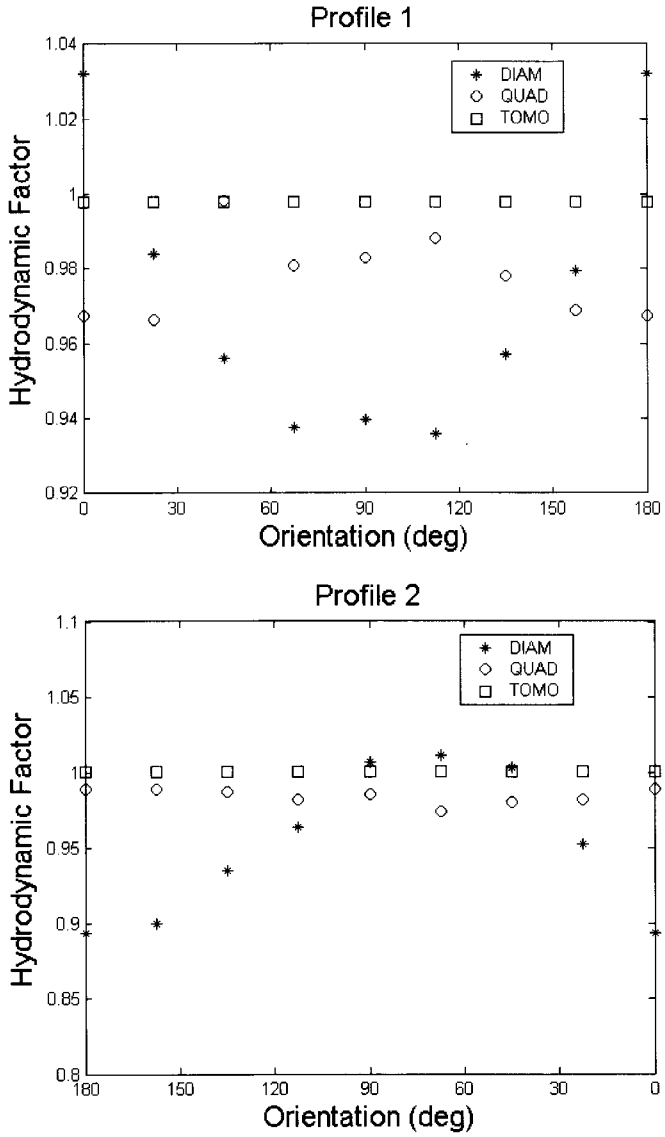

Fig. 7: Variation of hydrodynamic factors for the flow meter configurations, DIAM (diametrical), QUAD (quadrature) and TOMO (tomographic) on flow profiles 1 and 2.

The hydrodynamic factors for profiles 1 and 2 are shown in Figure 7. The hydrodynamic factor of the single path flow meter in a diametrical configuration has the largest variation with respect to orientation. The hydrodynamic factors of the tomographic configuration are relatively constant, and remain close to 1.0, with respect to orientation in an asymmetric flow, i.e., the actual velocity is almost equal to the measured velocity for orientation increments of 22.5°.

The orientation sensitivity factor calculated for the three configurations are listed in Table 2, and the values are very close to zero for the tomographic configuration. This shows that the hydrodynamic factor is constant for orientation increments of 22.5°. It is clear from the results that the tomographic ultrasonic flow meter can provide a more accurate measurement of flow velocity in asymmetric flows than the diametrical and quadrature configurations.

Table 2: Orientation sensitivity factors.

Configuration	Orientation sensitivity factor, *S*	
	Profile 1	*Profile 2*
DIAM	0.0914	0.1272
QUAD	0.0320	0.0149
TOMO	0.0000	0.0000

ing the flow velocity. From the measurements, the average sound wave velocity is found to be 334.7 m/s.
The average axial flow velocity was then calculated in each measurement path and the total average velocity was determined. The average axial flow velocity and the flow rate obtained from the experiments are described in Table 3.

Table 3: Measurement results obtained from the tomographic ultrasonic flow meter.

Experiment	**Average Velocity** (m/second)	**Flow Rate** (m^3/second)
I	0.867	0.028
II	1.579	0.051
III	2.277	0.074

In these experiments, the measurement result was not compared to a standard flow meter for validation. However, for comparison, the average velocity was also measured using a single path ultrasonic flow meter in the diametrical configuration. Table 4 shows the results obtained from both the diametrical and tomographic flow meters. The error is defined as the difference between the measurement results obtained from both these types of flow meter.
The measurement path of the diametrical flow meter is only along the diameter, while the tomographic flow meter has measurement paths in a variety of positions and directions. As discussed in section 3.2., the tomographic flow meter is more accurate than the diametrical flow meter. Thus, in these experiments, the error which occurs can be viewed as the relative error of a diametrical flow meter compared to a tomographic flow meter.
Before the velocity profile is reconstructed, the measurement path data are interpolated to be 40 and 240 equally spaced data in each projection. The reconstructed velocity profiles are shown in Figures 10 and 11. The result obtained from 240 interpolation projected data is better in terms of smoothness relative to the 40 interpolation projected data.

5 Conclusions

This paper has presented a new multi-path ultrasonic transit time flow meter with a tomographic configuration for measurement of the flow velocity profile. The proposed flow meter consists of a set of transmitting transducers and a set of receiving transducers placed at different positions on the pipe surroundings. The flow is electronically scanned by ultrasonic transducers, i.e., the transmitter is activated sequentially from the first transmitter to the last transmitter. This configuration results in an ultrasonic path in various directions and positions for detecting the flow, and makes it possible to estimate the flow velocity profile using the tomography approach. The transit time of an ultrasonic wave is measured in each measurement path and the weighting method is then used to calculate the total average velocity. The filtered back projection algorithm of the straight path tomography was employed for reconstructing the flow velocity profile. From the experimental results, the tomographic ultrasonic transit time flow meter can, in principle, be implemented for measuring both the total average flow velocity and the velocity profile. The tomography results show that the flow meter can be used to visualize the velocity profile. It has also been shown that the hydrodynamic factor of the tomographic ultrasonic flow meter was relatively constant, remaining close to 1.0 for orientation increments of 22.5°, and its sensitivity factors are zero. Thus, the tomographic ultrasonic flow meter can be used to provide more accurate measurements of flow velocity than the diametrical and quadrature configurations in asymmetric flows.

Table 4: Results from diametrical and tomographic flow meters.

	Average Velocity (m/second)			**Flow Rate** (m^3/second)		
	I	**II**	**III**	**I**	**II**	**III**
Single path (Diametrical)	1.024	1.717	2.417	0.033	0.056	0.078
Multi-path (Tomographic)	0.867	1.579	2.277	0.028	0.051	0.074
"error"	0.157	0.138	0.140	0.005	0.005	0.004

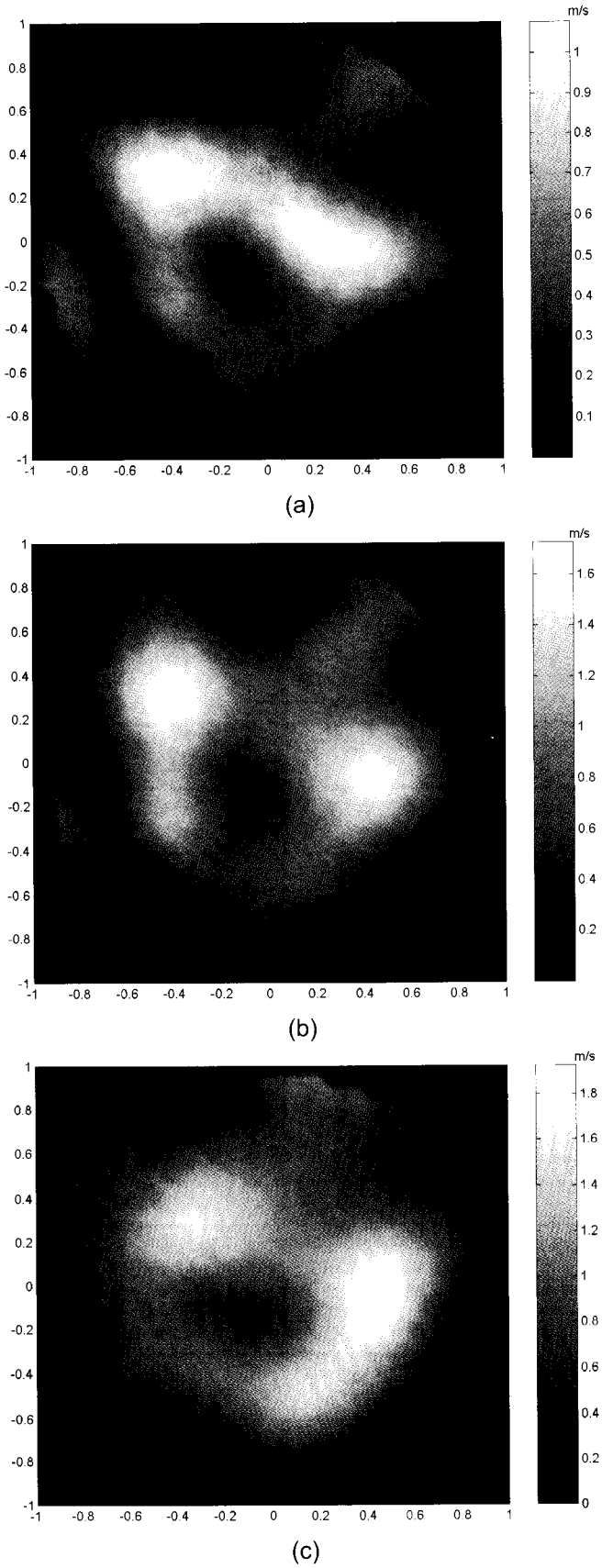

Fig. 10: Flow velocity profiles with 40 interpolated data.

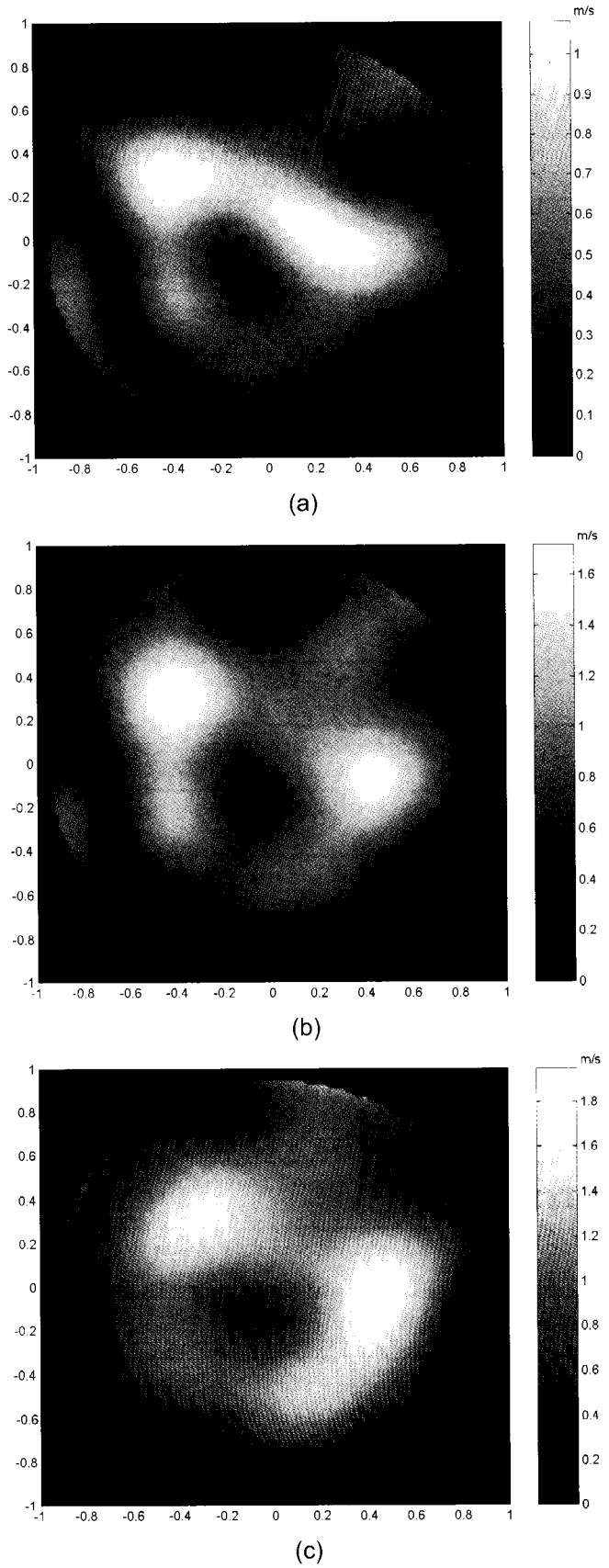

Fig. 11: Flow velocity profiles with 240 interpolated data.

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Erratum

The Use of an Exact Light-Scattering Theory for Spheroidal TiO2 Pigment Particles, Juho Jalava
Part. Part. Syst. Charact. 23 (2006) 159–164

Unfortunately in the Abstract of the paper a word (opacity) is missing.

In the first sentence in the Abstract:
... because of the excellent and whiteness they provide.

There should be:
... because of the excellent opacity and whiteness they provide.

