Velocity profile measurement by ultrasound Doppler shift method

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The application of an external blood flowmeter, an ultrasonic Doppler shift detection device, to the one-dimensional velocity profile measurement of the general flow of water was studied. Experiments were carried out for Poiseuille flow in a 12 mm diameter pipe and for Taylor vortex flow in a roating double cylinder with a 5 mm gap. Measured velocity profiles showed good agreement with theoretical predictions, implying that the device works quite successfully for this purpose.

Keywords: *flow velocity profiles, flowmeters, ultrasonic Doppler shift*

Introduction

For heat transfer studies, knowledge of flow behaviour is obviously very important. Various methods and techniques have been applied in investigations especially related to nuclear, solar and fire research, where knowledge of flow patterns in enclosures is required. For these purposes flow visualization techniques have mainly been used, in order to obtain spatial information on flows. However, this method has the disadvantage of difficulties in obtaining quantitative results and real time data handling. Furthermore, its application to opaque fluids is not possible.

Laser Doppler anemometry is now quite popular for fluid flow research. Although this method gives a response time short enough for real time data acquisition, and resolution high enough for time-series information, it gives only pointwise information, which is of little use for studies of spatial structure of flows. Recently, an external blood flowmeter (EBF) has been developed in the medical field. This device uses the principle of Doppler shift of ultrasound to measure the profile of blood flow in a blood vessel, in order to give the time-dependent flow rate of blood. It employs the pulsed echo method, detecting the Doppler shift in the echo as a function of time after the pulse emission. Reflection of the ultrasound comes from the interface of blood cells. It gives spatial information on the velocity profile in a blood vessel within a short time, and hence the profiles as a function of time. In this work, an attempt was made to apply this device to flow measurement of general fluid. Two kinds of configuration were used with water. One is a Poiseuille flow in a simple pipe and another is a Taylor vortex flow. The former was selected because of its simplicity of flow and its well established theory. The latter was chosen because of its somewhat complicated but interesting velocity profile along the longitudinal direction and because of its experimental simplicity.

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Experimental apparatus

Principle of measurement

The EBF is a device to measure the time change of the flow rate of blood by the ultrasonic Doppler shift detection method. The principle of the method is illustrated in Fig 1 for the example of one-dimensional flow in a pipe or parallel plates. Fig 2 is a schematic diagram of its electronic circuit. A transducer is placed on a wall with an angle inclination θ to ensure a velocity component in the direction of the measuring line. A transmitter emits an ultrasonic pulse, the basic frequency of which is 4.2 MHz and pulse width 2 μs, repetition period 122 μs. Fig 1(b) shows an example of the signal of the received echo. Between two emissions of ultrasonic pulses the echo can be observed, backscattered from somewhere on the measuring line. A position axis along the measuring line is thus converted to a time axis. The frequency of an echo signal at any instant is Doppler-shifted due to the fluid motion as far as it is reflected inside the flow. After the amplification of this echo signal, it is demodulated to eliminate the component of basic frequency and then digitized. The sampling period of this digitization is fixed at 122–128 μs, implying that the maximum measurable length is divided into 128 channels. The time series of the digitized data is then filtered digitally to eliminate spurious frequency components which may arise from the vibration of the container or from noise, then the Doppler shifts are detected by counting up the zero-crossings for each channel, to give a histogram of velocity values, and thus the velocity profile (Fig 1(c)).

In the histogram, the position is determined from an echographic equation:

$$d = ct/2$$

where d is the distance from the transducer, c is the speed of ultrasound in the fluid, and t is the reception time.

From the Doppler shift frequency of each channel, velocity values can be calculated from the following Doppler equation:

$$V_i = \frac{V_i^{ML}}{\cos\theta} = \frac{c}{2f_0 \cos\theta} f_i^D$$

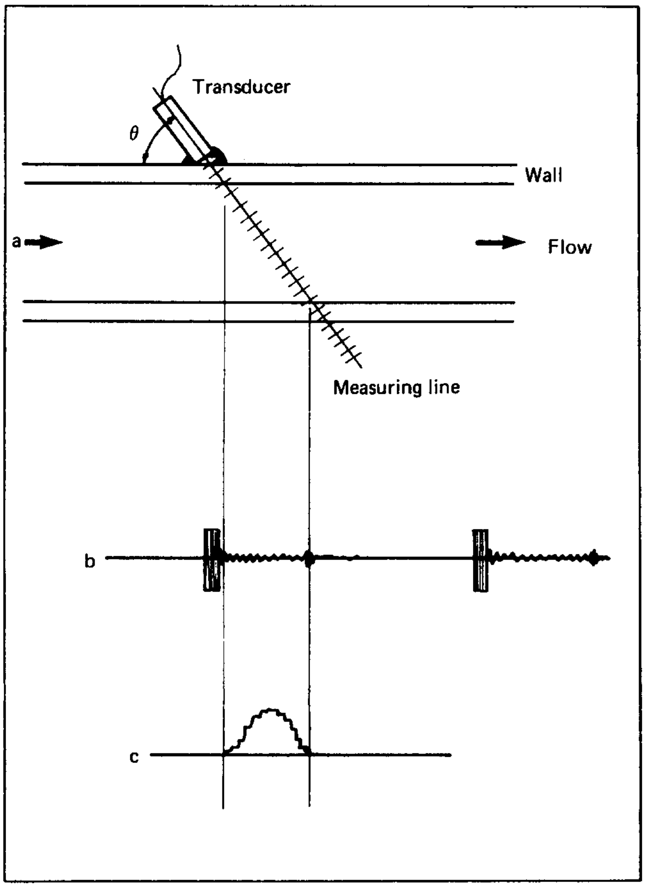

Fig 1 Principle of the method

where V_i is the velocity value at channel i; V_i^{ML} is the velocity component at each channel i in the direction of the measuring line; c is the speed of ultrasound in the fluid; f_0 is the basic ultrasound frequency; f_i^D is the Doppler frequency shift for channel i; θ is the angle between transducer and flow direction.

When the present device is used with water, the maximum measurable distance from the transducer is approximately 9.2 cm ($c = 1500$ m/s), with a position resolution of about 0.7 mm. With inclination angle of 60° the maximum measurable flow velocity is about 73.2 cm/s with a resolution of 0.6 cm/s. Since it measures only Doppler shift, reflections from the interface between fluid and the container wall do not affect the measured results. The data acquisition time to give one frame of profile is approximately 16ms. The size of the transducer used in this work is 4 mm in diameter. Since a prototype flowmeter was used, which was equipped only with a DAC output, the profiles obtained were displayed on the oscilloscope and photographs were taken of its display.

Poiseuille flow

A schematic layout of the experimental setup is illustrated in Fig 3. The inner diameter of the pipe is 12 mm and the entry length to the measuring point is 1.8 m. As a reflecting material, Al_2O_3 powder whose particle diameter size was approximately 5 μm was suspended in water. The part of the pipe at which the profile was measured was immersed in a water bath in order to have good contact between the transducer and the pipe and to eliminate the multiple reflection of ultrasound from the surroundings. The transducer was set at the angle of 60° with respect to the flow. Flow rate was measured by weighing the water quantity.

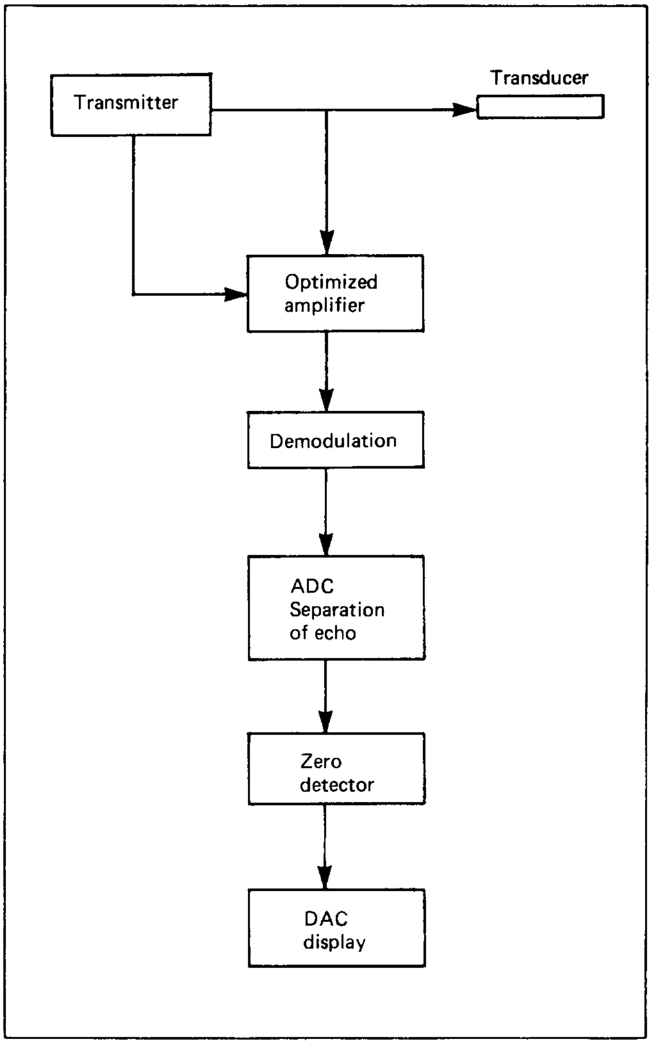

Fig 2 Schematic diagram of electronic circuit

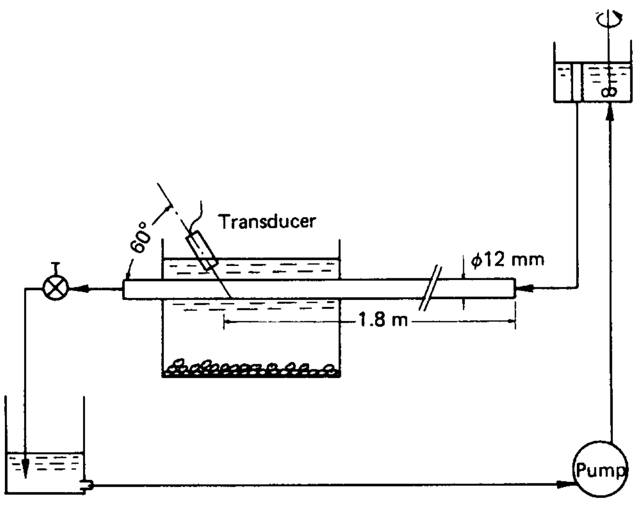

Fig 3 Schematic layout of experimental setup for Poiseuille flow

Taylor vortex flow

The experiments were carried out in a rotating double cylinder. The diameters of the inner and outer cylinders were 10 and 11 cm, respectively, and the height of the water layer was 6.0 cm. The outer cylinder was fixed and only the inner one was rotated. The rotation speed, set by observing the flow, was such that the *Ta* number was definitely beyond the critical value for the production of a roll structure. The axial velocity profile was measured by setting the transducer vertically upward on the bottom face of the container. Two measurements were performed for one rotation speed, one along the outer surface and another along the inner.

Experimental results and discussion

Poiseuille flow

Fig 4 shows a typical example ($Re = 1945$) of a measured profile. The lower line is an echo signal and the upper one is a velocity profile converted from the Doppler shift frequency of the echo. The profile has a histogram structure due to the digitization of the echo signal. It shows a parabolic distribution of velocity. The width is 14.1 mm, which agrees quite well with the path length of ultrasound in the pipe (13.9 mm). However, it was observed that this profile changes its height and its shape from picture to picture although every picture showed an essentially parabolic distribution with little change of width. This amplitude variation and deformation of profile arise partially because the amount of reflecting powder is not optimum and partially because of its density fluctuation. Accumulating 25 to 50 frames of these pictures leads to a smoothed average of the profile (Fig 5). The remaining 20% fluctuation of the peak velocity in this case is presumably due to variation in the flow velocity itself. In this simple experimental arrangement a stirrer was used to mix the powder uniformly in the top reservoir, and no special care was taken to stabilize the water level. Reading the average voltage values on a picture gives a numerical velocity profile. Fig 6 shows the profiles for $Re = 2125$ and 902. These profiles were fitted to a parabolic function by a least-square method, which reproduced the data quite well. The *Re* numbers derived

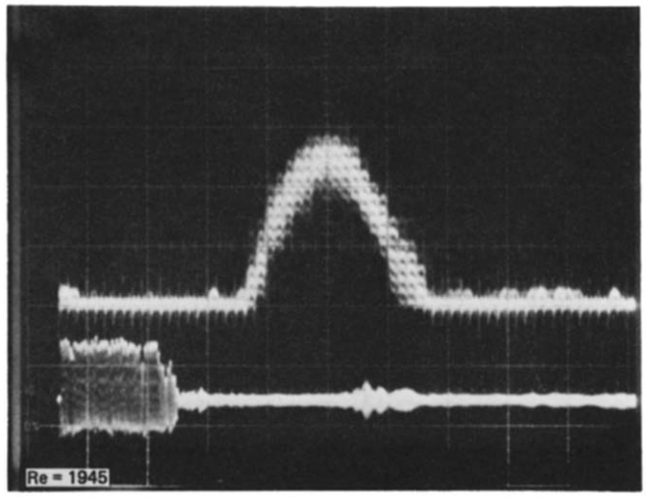

Fig 5 Same as Fig 4, but smeared for 50 pictures

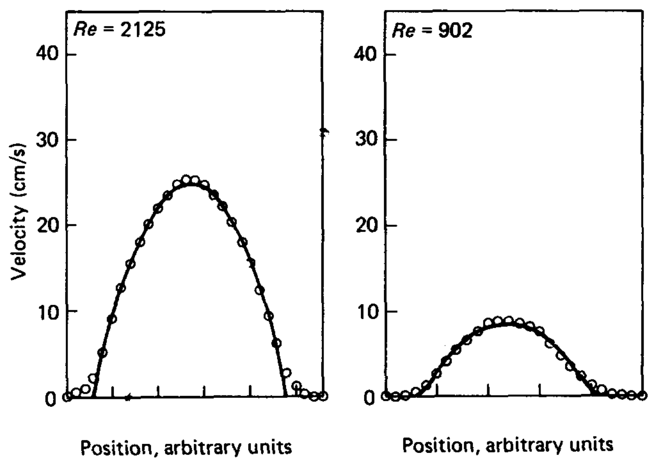

Fig 6 Measured profile for Poiseuille flow and parabolic fitting

from the fitted data are 1539 and 547 with differences of 28% and 40% respectively from the value obtained from flow rate measurements. Considering the condition of nonoptimum amount of reflecting particles, and the diameter of the transducer and pipe, the present method tends to give lower values of velocity, so that the outer envelope containing all the fluctuations corresponds rather to the profile on the plane which goes through the centre line of the pipe. This leads to *Re* numbers of 1747 and 728, reducing the difference to 17 and 19%. This is then in reasonable agreement, in view of the limited accuracy of the mass flow measurement. The flowrate measured in this work was an average over a few minutes whereas the velocity value derived from the profile gives an instantaneous value. It can be expected that the fluctuation of flow during those few minutes would cause the discrepancy in the determination of *Re* numbers. Fig 7 shows variations of the velocity profile for various *Re* numbers. As clearly seen, for *Re* numbers lower than 2145, profiles are parabolic but start to deform from $Re = 4120$. Especially at $Re = 6565$ a very strong fluctuation appears on the tail side of the profile. This may be due to the internal motion of Al_2O_3 powder in the turbulent motion of the fluid and the resulting multiple reflection of

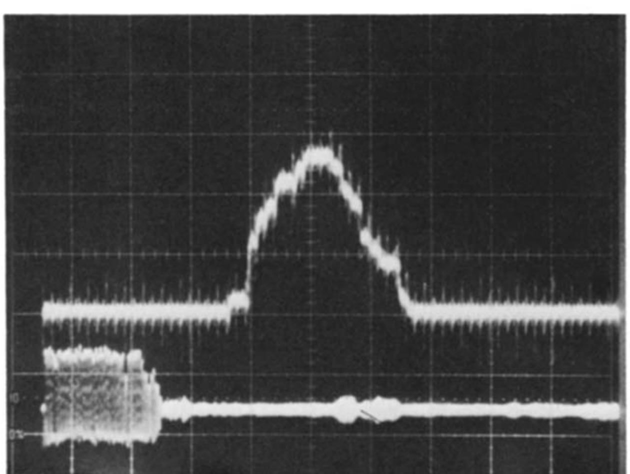

Fig 4 Oscilloscope output: echo and Doppler shift profile for Poiseuille flow (Re = *2125*)

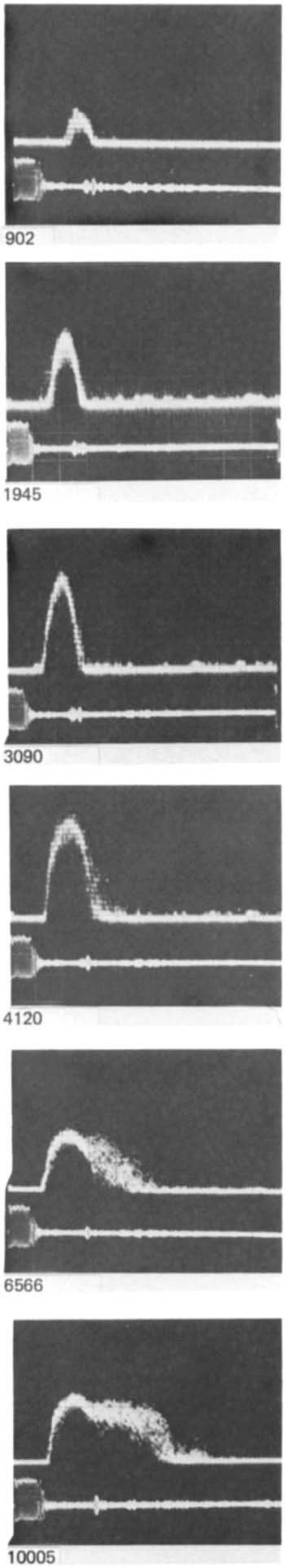

Fig 7 Comparison of velocity profiles of Poiseuille flow for various Re *numbers*

ultrasound in the tube. The front part of the profile shows much less fluctuation. Voltage values of this part of the profile was read and converted to a velocity profile, and it was fitted to a power law distribution. The calculated value of the power was 0.137 and shows quite good agreement with the 1/7 power law of turbulent velocity distribution in a pipe for this range of *Re* number.

Taylor vortex flow

Fig 8 is an illustration of a typical vertical cross-section of the roll structure in a Taylor vortex flow in a rotating

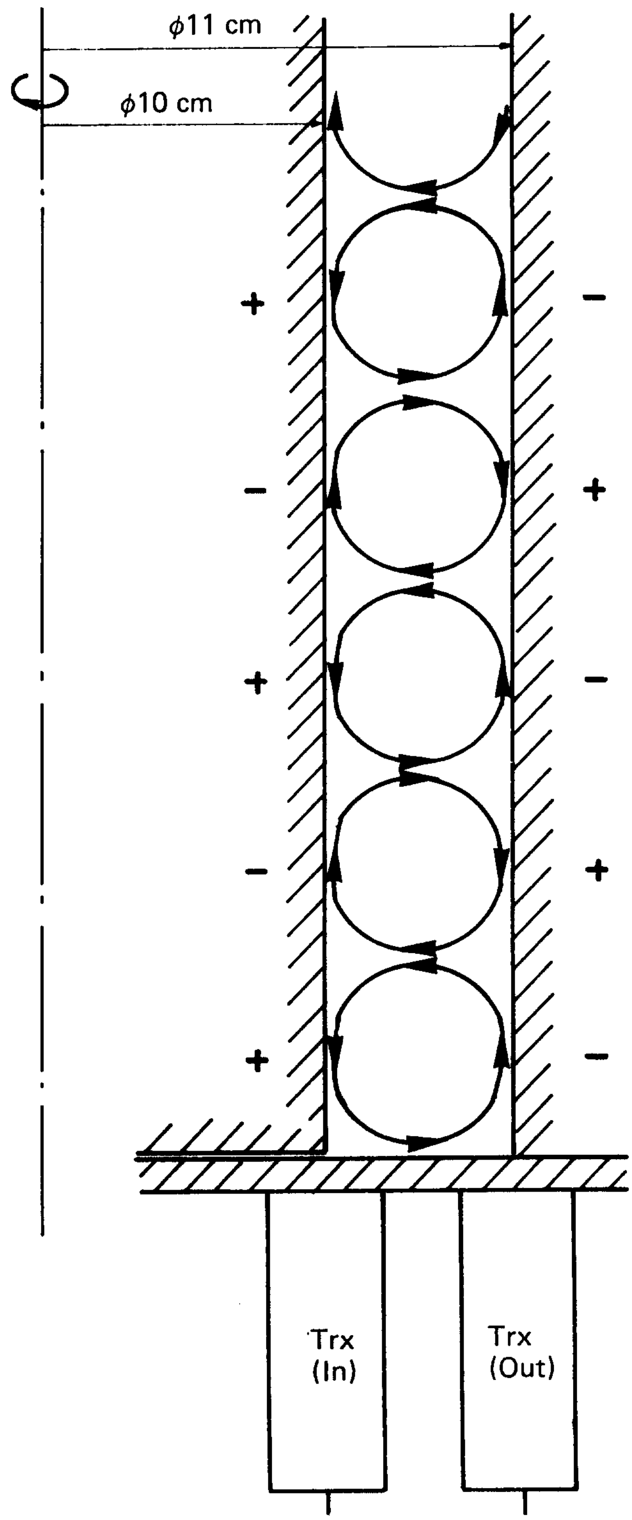

Fig 8 Roll structure of Taylor vortex

double cylinder. Fig 9 is a measured profile of the longitudinal velocity for *Ta* = 2066, where (a) is the outside surface of the gap and (b) is the inside. On the echo signal the reflection from the top surface is recorded and it can be used for calibrating the distance on the picture. Oscillatory behaviour is clearly obtained. As seen in Fig 8, the velocity along one boundary reverses its direction from roll to roll. Moreover, on both boundaries at the same height, the velocity has the same amplitude but with opposite signs. The phases of both measured profiles are opposite to each other, which implies that the velocity is opposite and demonstrates the roll structure of the flow. For this *Ta* number, the rolls are not fully established in the middle part of the system. In this region the velocity has actually decreased below detection threshold. However, on the upper and lower part of the system the roll structure is well developed. These profiles were also read and the velocity profiles were reconstructed and plotted in Fig 10. This structure is in good agreement with the theoretical calculation of Ref 2. The distance between two crossings of the zero line correspond to the size of one roll. It gives an aspect ratio for the cross-section of a roll of about 1.2, which also agrees fairly well with Ref 2.

Conclusion

By making use of the external blood flowmeter, which is a stand-alone machine for medical use, the feasibility of the application of a Doppler shift ultrasonic technique to velocity profile measurement. It is concluded that, in principle, the device is applicable for this purpose.

The advantage of this method is that spatial information on flow behaviour can be obtained instantaneously. The accuracy of the velocity

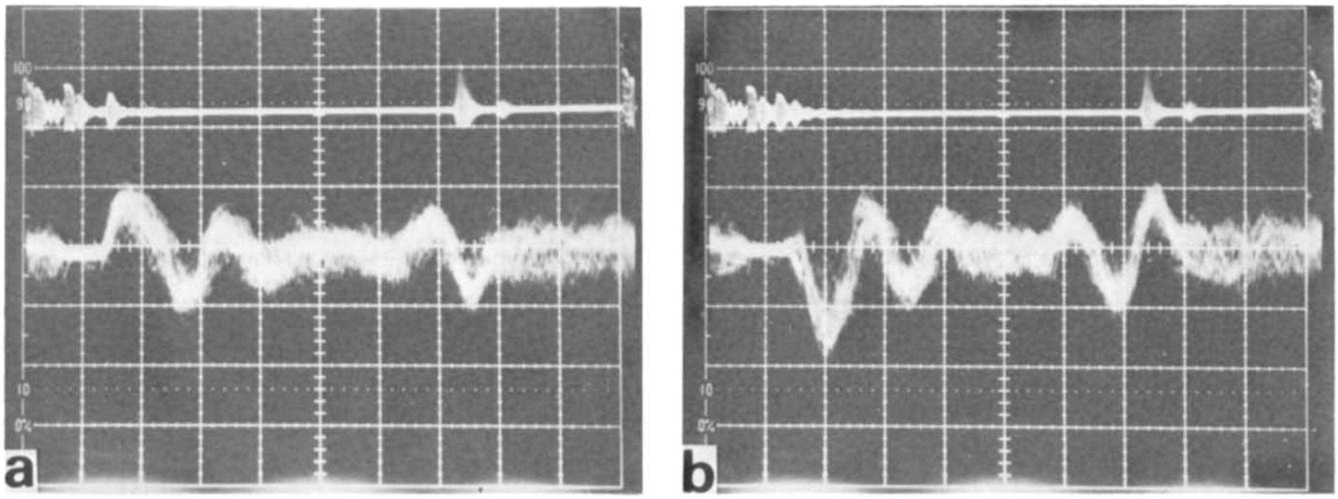

Fig 9 Profile of longitudinal velocity for Taylor vortex flow (Ta = *2066*)*: (a) outside of gap; (b) inside*

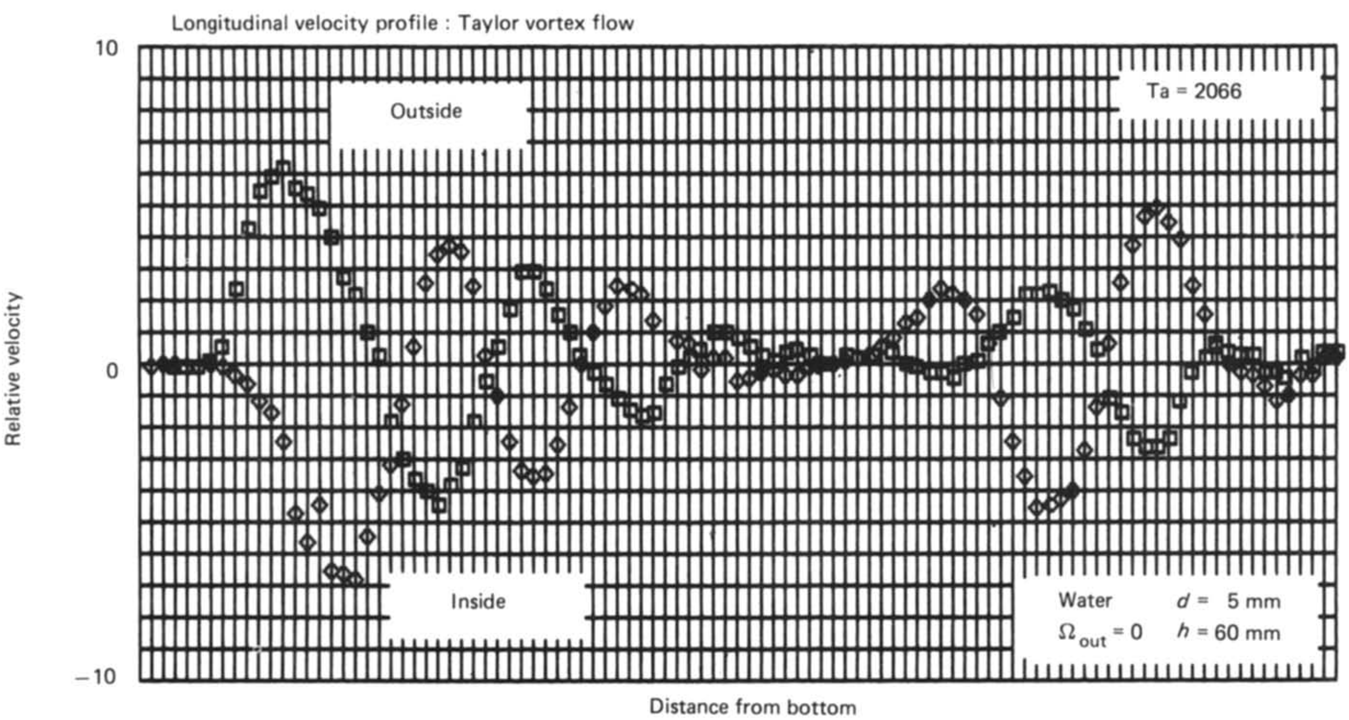

Fig 10 Measured vertical velocity profile of Taylor vortex (Ta = *2066*)

measurement and the resolution in position and time are deeply related to the selection of frequency of ultrasound, its pulse structure and electronic constants for data acquisition. They can be adapted to the requirements of various different cases. The limitations of the method arise first from the fundamental properties of ultrasound, namely that the measurable depth is limited by the attenuation of ultrasound. Furthermore, the method requires some amount of reflecting particles suspended in the liquid, which may disturb its flow or change its fundamental properties.

Although the device was developed for measurement of one-dimensional flow, profiles can also be successfully obtained for flow which is essentially multi-dimensional. Considering its principle, it would be promising to apply the same method to opaque fluids such as liquid metals.

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References

1. **Meister J. J.** Mesure par echographie Doppler et modelisation theorique de l'effet de troubles cardiaques sur la pression et le debit arteriels. *These No. 504, 1983, Ecole Polytechnique Federale de Lausanne*
2. **Alziary de Roquefort T. and Grillaud G.** *Computers and Fluids, 1978,* **6**, *259*

CALENDAR

1987		
Valve technology	26–28 January 1987 Amsterdam, The Netherlands	The Center for Professional Advancement, Palestrinastraat 1, 1071 LC Amsterdam, The Netherlands
Pressure vessel design and analysis	16–19 February 1987 Amsterdam, The Netherlands	The Center for Professional Advancement, Palestrinastraat 1, 1071 LC Amsterdam, The Netherlands
10th BPMA Technical conference on pumps	24–26 March 1987 Cambridge, UK	BHRA Fluid Engineering Centre, Cranfield, Bedford MK43 0AJ, UK
Large scale applications of heat pumps	25–27 March 1987 Oxford, UK	BHRA Fluid Engineering Centre, Cranfield, Bedford MK43 0AJ, UK
11th international conference on fluid sealing	8–10 April 1987 Cannes, France	BHRA Fluid Engineering Centre, Cranfield, Bedford MK43 0AJ, UK
International meeting on heat transfer	13–17 April 1987 Lyon, France	Professor J. F. Sacadura, INSA de Lyon, LMFT Bat. 302-20 Ave. Albert Einstein, 69621 Villeurbanne Cedex, France
1987 IEA Heat pump conference	28–30 April 1987 Orlando, Florida, USA	Ms Pamela J. Lewis, Oak Ridge National Laboratory Building 9102-2, PO Box Y, Oak Ridge, Tennessee 37831, USA
International conference on flow induced vibrations	12–14 May 1987 Bowness-on-Windermere, UK	BHRA Fluid Engineering Centre, Cranfield, Bedford MK43 0AJ, UK
3rd international conference on multi-phase flow	18–20 May 1987 The Hague, The Netherlands	BHRA Fluid Engineering Centre, Cranfield, Bedford MK43 0AJ, UK
32nd ASME International gas turbine conference and exhibit	31 May–4 June 1987 Anaheim, California, USA	IGTC, 4250 Perimeter Park South, #108 Atlanta, Georgia, 30341, USA
Twentieth Midwestern mechanics conference (20th MMC)	31 August–2 September 1987 Indiana, USA	Professor Hamilton, School of Mechanical Engineering, Purdue University, West Lafayette, Indiana 47907, USA
1987 ASME cogen-turbo	2–4 September 1987 Montreux, Switzerland	IGTC, 4250 Perimeter Park South, #108 Atlanta, Georgia 3041, USA
6th turbulent shear flow symposium	7–9 September 1987 Toulouse, France	Professor F. W. Schmidt, Secretary, Dept of Mechanical Engineering, The Pennsylvania State Univ., University Park, PA 16802, USA
Second international conference on laser anemometry	21–23 September 1987 Glasgow, Scotland, UK	Dr S. M. Fraser, LDA Conference, Mechanical and Offshore Engineering, University of Strathclyde, Glasgow G1 1XJ, UK
International symposium on natural circulation	15–20 November 1987 New York, NY, USA	Dr J. H. Kim, Electric Power Research Institute, PO Box 10412, Palo Alta, California 94303, USA
1988		
International fluid power exhibition	18–22 April 1988, Birmingham, UK	Mr Mike Wells, International Fluid Power, Exhibition, Station Approach, Long Lane, Hillingdon, Middlesex UB10 9NR, UK