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Effect of control volume of UVP method on turbulent pipe flow measurement

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1. Introduction

Measurement of an instantaneous velocity profile of the turbulent flow has long been demanded in fluid dynamics, fluid engineering and other engineering fields involving a fluid flow. Various flow visualization techniques have been used for measurement of flow characteristics and sophisticated image processing procedures such as Particle Image Velocimetry (PIV) or Particle Tracking Velocimetry (PTV) are now available. They require, however, experienced know-how for successful measurement and data treatment, and are still expensive and time costuming for measurement. Ultrasonic Velocity Profile (UVP) method has been developed by Takeda at Paul Scherrer Institut in Switzerland [1]. It utilizes a pulsed echo-graphic technique of ultrasound and can measure a velocity profile on a measuring line instantaneously. Since the spatial information of the flow field is obtained from its traveling time, this method has various advantages over other flow measuring methods for measurement.

Although UVP method can be adapted for various liquid flow velocity measurements, it is necessary for the measurement of turbulent flow to consider the effect of measuring control volume. That is, UVP method has large measuring control volume compared with other conventional methods. Even for LDA measurement of turbulent flow, there have still been several attempts described in literature to obtain the influence of the effective volume size. Therefore, the effective volume size of UVP method for velocity profile measurement on the turbulent pipe flow was studied in the work.

Reynolds stress measurement on the turbulent pipe flow using one-component measurement is available [2][3]. Considering the effective volume size, the Reynolds stress was investigated by mean of UVP method.

2. Effect of control volume and Reynolds stress measurements

2.1 Mean velocity

The principle of UVP is to detect and process the echoes of ultrasonic pulses reflected by micro-particles crossing the measuring control volume. If the control volume was negligibly small the mean velocity U would be obtained by

$$U(x_c) = \sum_{i=1}^{N} U(x_c, t) \ . \tag{1}$$

where x_c the position of the measuring control volume. However, the measuring control volume is of a finite size and also velocity gradients exist across it.

Thus, considering the UVP measuring control volume and measurement period,

$$< U_{MVx_c} > = \frac{1}{Vm\ \tau_w} \int_t \int_V U(x_c, t) dV dt \tag{2}$$

where, Vm is the measuring control volume τ_w is measurement period. It is well known that an error in turbulence measurements is induced specially in region of high velocity gradients.

For the UVP method, the control volume is disk shape of the height h and diameter D. Considering this disk control volume and expressing the time averaged velocity in a truncated Taylor series expansion around its value at the center of the measuring control volume

$$Uc_v = U(y_c) + \frac{1}{2} G \left(\frac{\partial^2 U}{\partial y^2} \right)_{x=x_c} + \text{h.o.t.} \tag{3}$$

$$G = \left(\frac{h^3}{12 \cos^3 \theta} + \frac{2}{3} R^2 h \frac{\sin^2 \theta}{\cos \theta} + \frac{R^3}{8} \pi \sin^3 \theta + \frac{h^2 R \pi \sin \theta}{8 \cos^2 \theta} \right) \Big/ \left(\frac{h}{\cos \theta} + \frac{\pi}{2} R \sin \theta \right)$$

where, y is direction of radius (distance from the wall) and R is D/2.

2.2 Reynolds stress

In the present study measurements were carried out for the Reynolds stress $\overline{uv}$. To estimate these quantities using UVP method it requires independent measurements of the u and v-velocity components and also at angle α and $-\beta$ with respect to the x-axis. It is often common practice to set α and $-\beta$. Using coordinate transformations, the instantaneous signals can be expressed in term of the velocity components (Fig.1).

$$\tilde{U} = \overline{U} + u \tag{4}$$

$$\tilde{V} = \overline{V} + v \tag{5}$$

$$\tilde{Q} = \tilde{U} \cos \alpha + \tilde{V} \sin \alpha \tag{6}$$

And the fluctuating signals in the fluctuating velocity components on two measuring lines are:

$$q_1 = v \cdot \cos \alpha + u \cdot \sin \alpha \tag{7}$$

$$q_2 = v \cdot \cos \beta - u \cdot \sin \beta \tag{8}$$

With the prior knowledge of the u and v-velocity components, and if $\alpha=\beta$, the following expressions provide the Reynolds stress $\overline{uv}$.

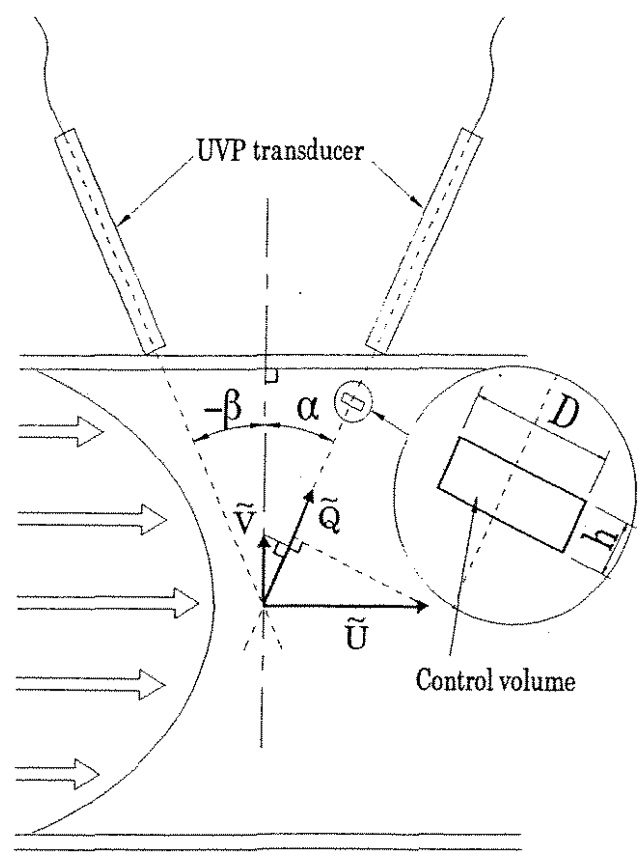

Fig.1 Control volume arrangements for measuring the Reynolds stress

$$\overline{uv} = \frac{\overline{q_1^2} - \overline{q_2^2}}{2 \sin 2\alpha} = \frac{q_1'^2 - q_2'^2}{2 \sin 2\alpha} \tag{9}$$

where, q' = standard deviation of the measuring line direction.

It should be notes that the above-described method is applicable only for steady flows.

3. Experimental set-up

A schematic diagram of the experimental apparatus employed in this study, is shown in Fig.2. Both water upward and downward flows can be investigated in the apparatus, which consists of a water circulation system, an air supply system, a test section and a measurement system. An air supply system is used for the two-phase flow and is composed of an air compressor, an air regulator for controlled to presser, an laminar flowmeter, and an air-water mixing section including injected needles (inner diameter: 0.1mm). In the present study, the downward flow for a single-phase turbulent pipe flow is studied. The water is contained in a storage tank, and is pumped up to an overflow tank by a centrifugal pump. Then it is fed into the test section through the contraction under a constant pressure. Flow rate is controlled by a needle valve and is monitored by two orifice flowmeters, one is used for Re<8000 and other one for Re≧8000. They are located downstream of the test section. During the experiments, water temperature is kept about 20 degrees using a sub-cooler. The flow measuring system consists of the UVP monitor (X-3 PS-i model) and a personal computer which records the flow rate and temperature data. Setting parameters of UVP measurement in present experiments are shown in Table1.

The test pipe made of Plexiglas of total 6m length is located vertically, and it is inner diameter is 50mm. The test section is located at 80 pipe inner diameters downstream of the entrance. Turbulence mixing is promoted by the "Tripping ring" mounted at the inlet pipe and thus to reduce the length required for fully developed turbulent flow.

The test section is shown in Fig.3. The UVP transducer is set on the surface of outer wall with a contact angle of θ degrees perpendicular to the flow direction. Wall thickness of pipe in this section is 1mm, because permeability of the ultrasonic beams are good. The test section is set in an aquarium filled with water to get easy and firm coupling between the wall and transducer. As a reflector material, nylon powder is suspended in water about 0.0058%vol which has a median diameter of about 80 μm.

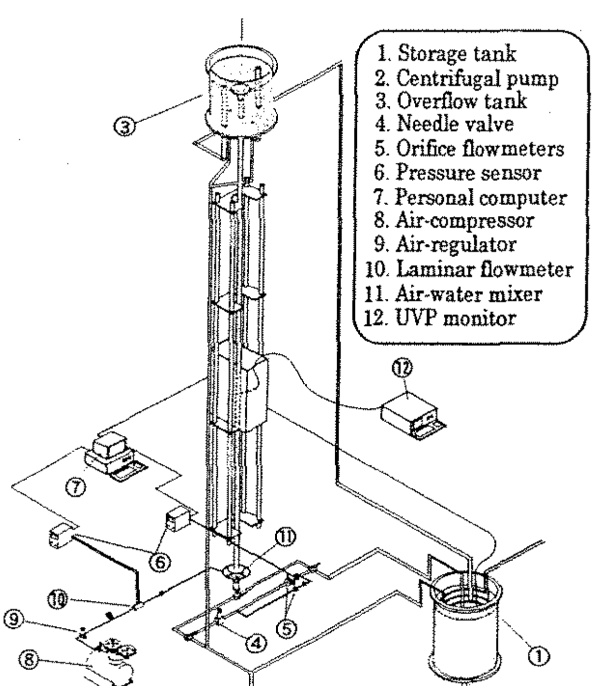

Fig.2 Schematic diagram of experimental apparatus

Table1 Parameters of UVP measurement

Basic ultrasonic frequency	4MHz
Maximum measurable depth	586mm
Velocity resolution	0.46mm/sec
Time resolution	147msec
Spatial resolution	0.37mm
Measurement point	128
Number of profiles	20000
Ultrasonic beam diameter	2.5mm

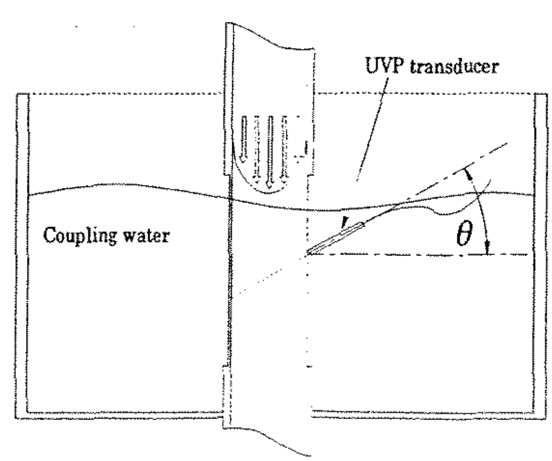

Fig.3 Test section

4. Experimental results

The error induced by the effect of measuring control volume is shown in Fig.4, which are based on the Direct Numerical Simulation [4]. Due to the error, depend on a curvature of velocity gradient, there are slightly different in the buffer region of $Y^+>30$ and $Y^+<2$. In region of $2<Y^+<30$, there are observed obvious deviation (max 5% at $\theta=15°$), and are increased with increase of θ. Further, the measuring control volume is crossed into the wall in the extremely near wall region. Therefore, nearest measuring point from the wall is $Y^+>3.6$ at $\theta=15°$. Measured mean velocity distribution in the present experiment at Re=5300 is shown in Fig.5. This velocity profile is sufficiently practical in $Y^+>30$ region. However, in $Y^+<3.6$ region is not accurately due to various effects as mentioned above and diffusion of ultrasonic pulse reflection from the wall and the error in $3.6<Y^+<30$ region is included by the effect of control volume.

The Reynolds shear stress profile over the pipe radius along with the data of DNS is shown in Fig.6. The present results are slightly smaller than those of DNS data in the region of $0.2 < r/R < 1.0$ and show a different near-wall profile.

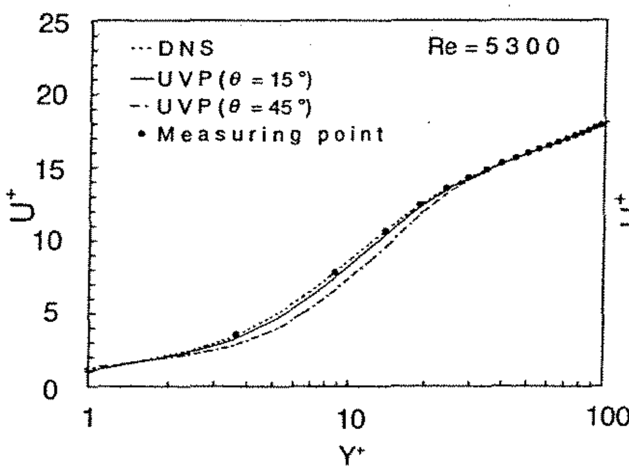

Fig.4 Effect of control volume on mean velocity profile

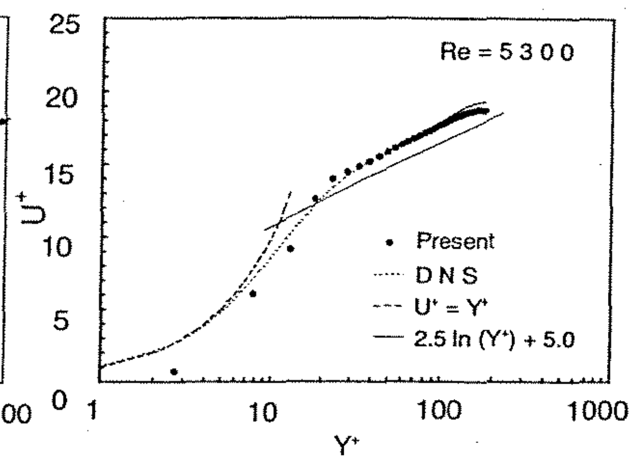

Fig.5 Mean velocity profile

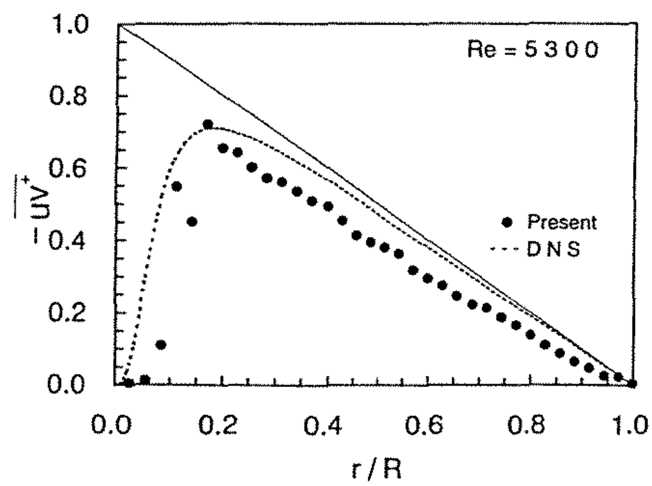

Fig.6 Reynolds stress

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