LASER ULTRASONIC FOR MEASUREMENTS OF VELOCITY DISTRIBUTION IN PIPES

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ABSTRACT

The present work describes the development of a photoacoustic flowmeter with probe-beam deflection. A pulsed laser beam produces an acoustic pulse, whose propagation is registered by its deflection effects on two cw probe beams. The acoustic pulse in a flowing fluid is produced by absorption of a laser pulse (30 ns, 1.1 mJ) focused over a path flow line. The acoustic propagations, along and against the flow, are monitored by two cw probe beams. In the interaction, the probe beam undergoes a transient deflection that is detected by a fast response photodiode. The velocity distribution data profile of a square pipe is obtained by means of the acoustic pulse arrival time measured through its cross section applying the cylindrical shockwave model developed by Vlasses. The profiles determined with this experimental technique are compared with two turbulent pipe flow models.

RESUMEN

El presente trabajo describe el desarrollo de un velocímetro fotoacústico para fluidos utilizando deflectometría. El sistema de medición está basado en la detección de un pulso acústico, producido por la absorción de un pulso láser (30 ns, 1.1 mJ) que es enfocado en una línea de corriente del flujo. La propagación del pulso es registrada, aguas arriba y aguas abajo, mediante dos haces continuos que sufren una deflexión cuando interactúan con la onda acústica que es detectada por un fotodiodo rápido. De esta manera, el perfil de velocidades de una tubería de sección cuadrada es encontrado mediante el tiempo de arribo del pulso acústico medido en su sección transversal, aplicando el modelo de onda de choque cilíndrica desarrollado por Vlasses. Los perfiles obtenidos con los valores experimentales son comparados con dos modelos de flujo turbulento aplicados en tuberías.

KEYWORDS: Velocimetry; Turbulent pipe flow; Laser-induced blast waves.

1. INTRODUCTION

Hot wire anemometry (HWA) [1], Laser Doppler Anemometry (LDA) [2] and Particle Imaging Velocimetry (PIV) [3] are relative well-established tools for the flow studies, but each of them possesses certain limitations. On the other hand, Digital Particle Imaging velocimetry (DPIV) [4] and Holographic Particle Imaging Velocimetry (HPIV) [5], are now more attractive to fluid dynamists due to its three-dimensional (3-D) full-field measuring capability and because it enables an instantaneous flow pattern to be captured in a pseudo real-time manner. There are other methods that use nonlinear optical effects, such as: Coherent Anti-Stokes Raman Spectroscopy (CARS) [6] or Stimulated Raman Gain Spectroscopy (SRGS) [7]. All LDV methods require the presence of light-scattering particles, and so are not applicable for pure gases.

CARS and SRGS methods have comparatively poor velocity resolution of typically 30 m/s. Thus, Zapka and Tam [8, 9] showed that the flow velocity of a pure particle-free gas could be measured to an accuracy of 5 cm/s by means of a laser-induced acoustic source. Such non-contact measurements were not possible previously by other known laser scattering methods.

In fluid mechanics, a pipe flow is two-dimensional. Therefore, it is well suited for investigation of fluid phenomena in internal flows, such as drag reduction and the bursting phenomenon. In many technological systems, thermal-stratified flow in a cylindrical tube is often encountered and it is important to investigate the heat and momentum transfer mechanism in such flow geometry [10]. This article presents the velocity distribution measurements in a high Reynolds number pipe flow by means of photoacoustic technique. This experimental velocity distribution is compared with n-root law for turbulent pipe flow model.

2. EXPERIMENTAL SET UP

The schematic diagram of the experimental arrangement for pipe investigation, using a laser-induced acoustic source and two cw probe beams, is shown in Fig 1. The acrylic (transparent) pipe is about 40 cm long with an internal square section of 5x5 cm^2 and 4 mm of thickness. The test section is located 1.8 diameters from the inlet in order to obtain a fully steady state flow. The flow would be fully developed in the test section when the mean pressure distribution along the pipe is almost constant.

A Q-switched Nd:YAG laser (Continuum, model Surelite I) was used as a standard source of ultrasound. Generating pulses of ≈ 20 ns, operated at a repetition rate of 10 Hz and output pulse energy ranging from 20 to 25 mJ per pulse at a wavelength of 532 nm. The laser energy was monitored by a pyroelectric detector (Lab Master Ultima, with P10i detector) from Coherent Inc. A fast photodiode with rise time < 2 ns from LaserOptics S.A. (V 0111.00), which receives part of the laser beam, was used to trigger the oscilloscope. The laser pulse was focused into a streamline in order to produce a focused spot on the middle pipe section, using a lens of 75 mm focal length. The probe lasers are two cw diode lasers from Coherent (model 0221-035-50). The acoustic pulse altered by the flow velocity arrives at two different probe beam locations (separated by distance ΔL, indicated in Fig. 1) causing a transient deflection, which is detected by a knife-edge and photodiode assembly.

The signals are acquired and recorded by an oscilloscope (Tektronix TDS540A). The subsequent signals analysis are processed in a PC.

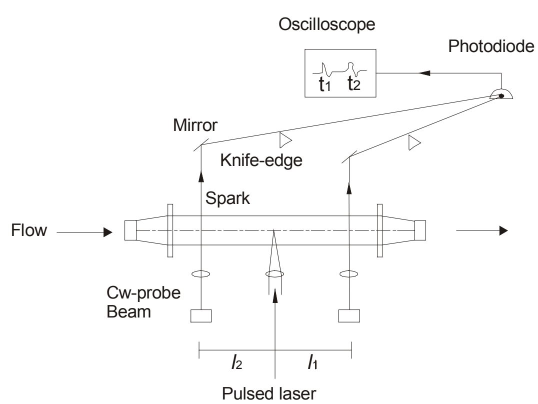

Figure 1. Experimental arrangement for photoacoustic monitoring of flow velocity profile in a water pipe

To measure the velocity profile, the acrylic pipe with square cross section is fixed on the vertical translation stage, which is movable orthogonal to the excitation beam direction; each probe beam is always parallel to the excitation beam. Subsequently, the translation stage is moved to another position through the pipe vertical axis (y direction).

The flow was driven by circulating pump from F&Q Pumps (model HT300, 3/4 HP).

3. EXPERIMENTAL RECORDING AND RECONSTRUCTION OF VELOCITY PROFILE

3.1 Basic principles

The basic principle of operation for this technique can be explained as follows. The focused pulsed laser produce blast or shock wave at 0, with the propagation velocity C(t) in the static fluid being time dependent and faster than the amplitude sound velocity of the medium C_0. The acoustic propagations downstream and upstream are:

$$R(t_1) + U(y)\cdot t_1 = l_1, \tag{1}$$

$$R(t_2) - U(y)\cdot t_2 = l_2, \tag{2}$$

where $R(t)=\int_0^t c(t')dt'$ is the range of the acoustic pulse in the static medium, and l_1, l_2 are the distances from 0. These are used to monitor the acoustic pulse at the arrival times of t_1 and t_2 respectively, and $U(y)$ is the flow velocity.

For a cylindrical blast wave, the propagation is given by [11]:

$$R(t) = C_0 \cdot t\left[1 + Ro/(C_0 \cdot t)\right]^{1/2} \quad , \tag{3}$$

where R_0 is a scaling length which depends simply on three quantities: C_0, fluid density, and the energy deposited per unit length in the acoustic line source. Equations (1), (2) and (3) all together give:

$$U(y) = \frac{C_0(t_2 - t_1)}{t_1 + t_2}(1+\delta) + \frac{(l_1 - l_2)}{t_1 + t_2} \quad , \tag{4}$$

This equation was published by Zapka and Tam [8], the blast wave effects are taken into account on the parameter δ, that is defined as $\delta = R_0^{\,2} / (8C_0^{\,2}\, t_1 \cdot t_2) \approx R_0 2/8 l_1 l_2$, and it is known as "blast wave correction".

In our experimental conditions, $R_0 \approx 0.387 \pm 0.08\text{cm}$ and $C_0 = 1{,}492 \pm 7$ m/s, these values were experimentally determined measuring the arrival time of the acoustical signals at different distances from the applied pulse in a static medium. This measurements give us the function $R(t)$. Fitting this experimental values in the equation (3) we can find R_0 and C_0 using a nonlinear least-square procedure. The numerical iteration was realized approximately 200 times and the overall error was about 0.05%. The software Origin 6™* was used for this solution. The results are shown in Fig 2. The dash line represents the theoretical curve of Eq. (1) for cylindrical blast wave with $R_0 = 0.0038$ m. It agrees with the experimental data very well for the range > 1 cm. In this case, for l_1, l_2 equal to eleven cm, the last equation implies that $\delta \approx 0.00132$; therefore, the correction δ can be neglected in our present measurements. The energy density applied for this case was of $165\text{x}10^{12}$ W/m^2. Its displacement from the acoustics source 0 is varied to obtain the relation between the range R of the acoustic pulse and the arrival time t in a static medium

* Trade Mark.

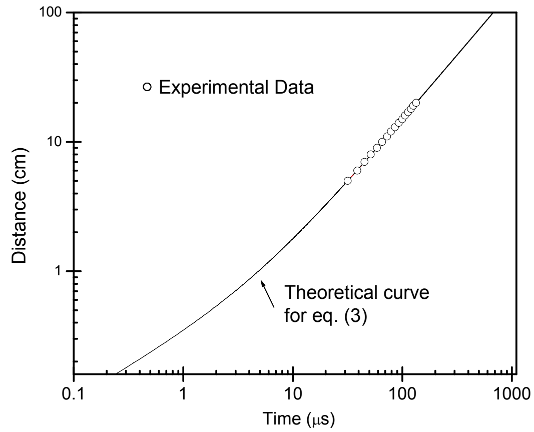

Figure 2. Cylindrical blast wase formula

3.2 Arrival time measurements and velocity profile

The velocity data were calculated with equation (4), introducing the first arrival times delay with respect to the trigger laser pulse, and the distance between the source and the probe beams l_1 and l_2.

In order to ensure reliability of the results, each test was repeated five times for each position, keeping constant (11cm) the distances between the acoustic source (0) and l_1 and l_2. All waveforms recorded during the tests were obtained using the average mode for 3-5s, obtaining 50,000 points for each waveform with a sampling rate of 250Ms/s. In Fig.3, where is presented a sample of deflection observed through the square pipe as a function of time for vertical displacements of 3 mm, keeping the probe beam (l_2) at 11 cm, it can be seen the waveform fronts at different distances of the pipe boundary; getting all together a sharp profile.

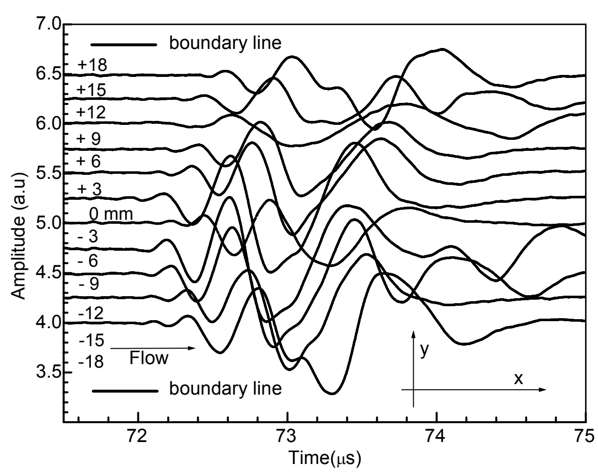

Figure 3. Example of deflection signals

The experimental velocity points were used in the n-root law for turbulent velocity distribution equation:

$$U(y) = U_{max}\left(\frac{y}{r_0}\right)^{\frac{1}{n}} \quad , \tag{5}$$

where: U(y): velocity, r_0: distance of the boundary from the pipe center, y: vertical position, and n: flow turbulence grade.

In this case: $U_{max} = 8.78 \pm 0.6$ m/s and $n = 3.25 \pm 0.9$. These values were obtained fitting a non-linear curve in Origin™ software. Fig. 4 shows both approximations: The values obtained with equation (4) by introducing the first arrival times for each position, in circle black dots; the n-root approximation, in dashed line; and fixed horizontal plates model, in circle empty dots. As it can be seen, these values indicate that the flow is not fully developed in the turbulent phase, however the main cuantily of the experimental points are between the two theoretical models.

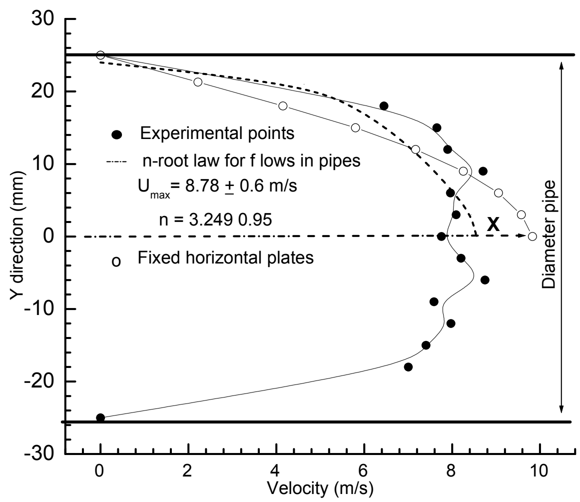

Figure 4. Velocity profile

4. CONCLUSIONS

A photoacoustic flowmeter with probe beam deflection has been developed to determine the flow velocity in a square pipe. Instantaneous two-dimensional velocity profiles can be extracted from the pipe flow. It is observed that the data experimentally obtained shows good agreement with those values obtained by using two theoretical models, reaching estimated accuracies of 15%. It is expected that significantly better velocity resolution will be obtained in future experiments using other oscilloscope with better resolution.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] Huelsz G., López-Alquicira F. Hot wire anemometry in acoustic wave, Exp. Fluids, Vol. 30 (3), 2001, pp. 283-285.
[2] McComb, W.D. and Chan, K.T. Laser Doppler anemometer measurements of turbulent structure in drag-reducing fiber suspensions, J. Fluid Mechanics, Vol. 152 (4), 1985, pp. 55-78.
[3] Grant, I. Particle imaging velocimetry: a review, Proc. Inst. Mech. Engrs (Part C), Vol. 211, 1997, pp. 55-76.
[4] Raffel, M., Willert, C., Kompenhans, J. Particle image velocimetry, a practical guide, New York : Springer, 1998.
[5] Chan, K. T., Li, Y. J. Pipe flow measurement by using a side-scattering holographic particle imaging technique, Optics & Laser Technology, Vol. 30, 1998, pp. 7-14.
[6] Gustafson, E. K., McDaniel, J. C. & Byer, R, L. Cars measurement of velocity in a supersonic jet, IEEE J. Quantum Electron, QE-17 (12), 1981, p. 2258.

[7] Herring G. C., Fairbank Jr. W. M and She C. Y. Observation and measurement of molecular flow using stimulated Raman gain spectroscopy, IEEE J. Quantum Electron, QE-17 (10), 1981, p. 1975.
[8] Zapka, W. and Tam, A. C. Photoacoustic pulse generation and probe-beam deflection for ultrasonic velocity measurements in liquids, Appl. Phys. Lett., Vol. 40 (4), 1982, pp. 310-312.
[9] Zapka, W. and Tam, A. C. Noncontact Optoacoustic determination of gas velocity and temperature simultaneously, Appl. Phys. Lett., Vol. 40 (12), 1982, pp. 1015-1017.
[10] Sakakibara, J., Hishida, K. & Maeda, M. Measurements of thermally stratified pipe flow using image-processing techniques, Exp. Fluids, Vol. 16, 1993, pp. 82-96.
[11] Vlases, J.C. & Junes, D.L. Blast wave from an inverse pinch machine the Phisics of Fluids, Vol 9, No 3, 1966, pp. 478-485.

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