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WALL SHEAR STRESS IN TURBULENT TRANSIENT FLOW

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ABSTRACT

Experimental measurements of the wall shear stress combined to those of the velocity profiles via the electrochemical technique and Ultrasonic pulsed Doppler Velocimetry, are used to analyse the flow behaviour in transient flow caused by a downstream short pipe valve closure. The Reynolds number of the steady flow based on the pipe diameter is Re = 121700. The results show that the quasi-steady approach of representing unsteady friction is valid during the initial phase for relatively large decelerations. For higher decelerations, the unsteady wall shear stress is consistently higher than the quasi-steady values obtained from the velocity profiles. An examination of the range of applicability of the instantaneous-acceleration model shows that the empirical coefficient of unsteady friction is closely linked to the deceleration intensity. This study is made possible owing to the repeatability of different valve closures allowing data to be averaged over numerous tests.

INTRODUCTION

Transient flows associated with the water hammer phenomenon are commonly encountered in both natural and engineering systems. Examples include water supply and distribution system, oil transportation system and human arterial network. The dramatic changes in velocity and pressure arising from these transient events can cause pipe breaks, flooding and other damage hazards. In engineering analysis of such flows, it is assumed that phenomenological expressions that relate the wall shear stress to cross sectional averaged velocity in steady state flows remain valid under unsteady conditions. In other words, a new Reynolds number is computed each time the velocity is altered and the wall shear stress is then adjusted to the value corresponding to stationary flows at the new Reynolds number. For example, the form of the Darcy-Weisbach equation used in water hammer models is:

$$\tau_w(t) = \frac{\rho\lambda(t)|V(t)|V(t)}{2} \qquad (1)$$

Where λ is the friction factor. The application of such a simplified wall shear stress model is satisfactory only for very slow transients, in which the shape of the instantaneous velocity profiles does not differ markedly from the corresponding steady-state ones. During fast transients or high frequency periodic flows, on the other hand, velocity profiles change in particular and more complex manners [1], showing greater gradients, hence, greater shear stresses, than the corresponding steady flow values.

NOMENCLATURE

a	[m/s]	Sound velocity
A	[m^2]	Active surface of the probe
C	[mol/m^3]	Bulk concentration
d	[m]	Pipe diameter
D	[m^2/s]	Diffusion coefficient
F	[-]	Faraday number
f	[Hz]	frequency
f_{PRF}	[Hz]	Pulse repetition frequency
I	[A]	Limiting diffusion current
k	[-]	Empirical coefficient of unsteady friction
K	[m/s]	Transfer coefficient
ℓ	[m]	Probe width
L	[m]	Pipe length
n_e	[-]	Number of electrons exchanged in a reaction
p	[m]	Fluid pressure
R	[m]	Pipe radius
Re	[-]	Reynolds number: Vd/ν
S	[1/s]	Velocity gradient at the wall
t	[s]	time
T_{PRF}	[s]	$1/f_{PRF}$
V	[m/s]	Mean axial velocity
Special characters		
λ	[-]	Friction factor
ν	[m^2/s]	Kinematic viscosity
ρ	[kg/m^3]	Fluid density
τ_w	[Pa]	Wall shear stress
τ_{ws}	[Pa]	Quasi-steady wall shear stress
τ_{wu}	[Pa]	Unsteady wall shear stress

A simple modification of equation (1) involves the introduction of an unsteady component $\tau_{wu}(t)$ such that:

$$\tau_w(t) = \tau_{ws}(t) + \tau_{wu}(t) \qquad (2)$$

Where $\tau_{wu}(t)$ is zero for steady flows, small for slow transients and significant for fast transients. Daily et al. [2] conducted laboratory experiments and found $\tau_{wu}(t)$ to be positive for accelerating flows and negative for decelerating flows. They argued that during acceleration, the central portion of the stream moved somewhat 'bodily' so that the velocity profile steepened, giving higher shear. The relation postulated by Daily et al. can be reformulated as follows:

$$\tau_w = \tau_{ws} + \frac{k\rho D}{8}\frac{dV}{dt} \qquad (3)$$

where *k*, an empirical parameter, needs be determined either from experiments or analysis. Daily et al. showed that *k* = 0.01 for accelerating flows and *k* = 0.62 for decelerating flows. The research of Shuy [3] led to *k* = -0.0825 for accelerating flows and *k* = -0.13 for decelerating flows. This illustrates that empirical constant k is flow case dependent. To explain these conflicting results, Vardy and Brown [4], argue that the different behaviours observed by the authors may be attributed to different time-scales.

The measurement of the unsteady wall shear stress so far were conducted in previous studies by measuring the wall drag force [3,5] or by determining the transient friction coefficient from the instantaneous mean flow velocity [6]. Whereas the above mentioned approaches are acceptable for flows accelerating or deceleration slowly at a uniform rate, they are questionable during fast transients. Moreover, the studies so far performed about transient flows are limited to quite narrow accelerations and deceleration ranges, and the results obtained by these studies are very different from one another.

From this brief review, it appears that direct measurements of the unsteady wall shear stress during fast transient flow, are greatly needed. It is shown that no conclusive result was obtained because of the scarcity of experimental wall shear data. A non-intrusive, local and quantitative method is actually greatly required to determine the important unsteady phenomena involved under transient conditions. The primary aim of this work was to examine the possibility of measuring the local unsteady wall shear stress within a decelerating turbulent flow in a short circular pipe. This is made possible by the use of the electrochemical method combined with the ultrasound velocimetry. Although the pipe length was rather short, it was able to provide fast transient flows characterized by complex shapes of instantaneous velocity profiles featuring annular effects leading to local flow reversal.

EXPERIMENTAL APPROACH

The electrochemical technique is now often used in order to measure the wall shear stress. A thorough review of the technique is provided by Hanratty and Campbell [7]. This method is based on the determination of the limiting diffusion current at the surface of an electrode under conditions for which the chemical reaction rate is fast enough so that the concentration of the reacting ions is null at the surface of the working electrode. If the length of this electrode is very small in the flow direction, the concentration boundary layer on the electrode is thin, thus the flow velocity varies linearly throughout the thickness of this boundary layer.

The current I flowing to the test electrode of area A is related to the mass transfer coefficient K by:

$$K = \frac{I}{A n_e F C_0} \qquad (4)$$

where n_e is the number of electrons involved in the reaction, F the Faraday constant and C_0 the bulk concentration of active species.

If the dimensionless velocity gradient at the wall $S^+ = \frac{S\ell^2}{D}$ (ℓ: electrode length, D: diffusion coefficient) is high enough, it is then possible to neglect the longitudinal diffusion, and a solution of the steady-state mass balance equation gives:

$$K^+ = \frac{K\ell}{D} = c\left(S^+\right)^{1/3} \qquad (5)$$

The integration of the mass transfer equation by several authors gives a theoretical value for the coefficient c in the case of a rectangular probe, c = 0.807.

When flush mounted mass transfer probes are used to measure wall shear rate of unsteady flows, featuring low velocity amplitude variations, a pseudo-steady state assumption can be made and the one-third-power law can be used to compute the instantaneous wall shear rate [8]. However, in many cases, the concentration boundary layer inertia cannot be neglected and the quasi-steady state assumption is not valid. Sobolik *et al.* [9] have introduced a technique based on the correction of the wall shear rate obtained from the Levêque solution by adding a term estimated from the known solution of the unsteady diffusion at the beginning of the potential transient process. This method is limited both to rather moderate frequencies and to non-reversing unsteady flows. In the presence of large unsteady or reverse flows, the inverse method ([10,11]) is more appropriate to calculate the wall shear rate from the mass transfer signal measured. Both methods have been used in the present study to correct the electrochemical signal.

EXPERIMENTAL APPARATUS

Experimental installation

Experiments were conducted in a vertical water channel (Figure 1). The main component is the *L* = 2.62 m long polypropylene pipe with a 61.4 mm internal diameter of and a *e* = 6.8 mm wall thickness. The pipe is connected to a supply and recycling system. A constant level tank is used to keep upstream pressures constant throughout measurements. A butterfly valve at the end of the pipe is used to create controlled opening and closing actions by adjusting the discharge into a free surface tank. More details of the experimental apparatus are reported in [12]. Pressure, velocity and wall shear stress are measured at a distance of 3.27 m from the free surface.

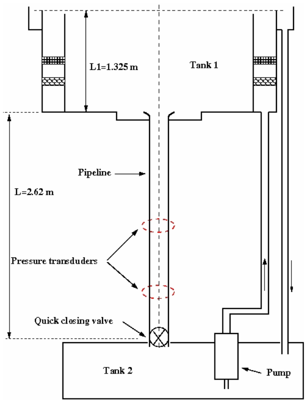

Figure 1 Experimental setup

Velocity measurements

In this study, the Ultrasonic pulsed Doppler velocimetry [13,14,15] was used for velocity profiles measurements. This method is based on detecting and processing the backscattered echoes originating from moving targets suspended in the flowing liquid that is to be investigated. This technique provides measurements of local one dimensional velocity and related distance from the transducer, leading to the setting up of an almost instantaneous velocity profile along the acoustic beam. The velocity component V_x of a particle in the direction of the acoustic beam is given by the relationship:

$$V_x = \frac{f_D}{2f} a \qquad (6)$$

Where f is the emitting frequency, f_D is the Doppler frequency shift that is due to the particle motion, and a is the sound velocity within the medium. The choice of ultrasonic scatters is crucial in the pulsed Ultrasonic Doppler velocimetry. Optimal particles have densities close to that of the liquid, so as to stay in suspension and follow the motions of the fluid. In this study, we use the copolyamide particles that are about 100 µm in diameter and 1.05 g/cm^3 in density.

Application of the electrochemical technique

The electrolytic solution is a mixture of potassium ferricyanide (10 mol/m^3) potassium ferrocyanide (10 mol/m^3) and potassium sulphate ((240 mol/m^3). The potassium sulphate acts as a low resistance vehicle for current flow and ensures that the transfer at the cathodic surface is controlled by diffusion only. The chemical reaction at the electrodes is described as :

$$\mathrm{Fe(CN)}_6^{3-} + e^- \longleftrightarrow \mathrm{Fe(CN)}_6^{4-}$$

All the experiments were carried out at 25°C. Under these conditions the physical properties of the electrochemical solution take the values given in Table 1. According to these values, the Schmidt number is 1375. The test electrodes were constructed by inserting a platinum sheet through the wall and gluing it in place. The rectangular electrode length and width is 0.1 mm and 0.5 mm, respectively.

Density, ρ (Kg/m^3)	1024
Kinematic viscosity, ν(m^{2}s^{-1})	1.025 10^{-6}
Diffusivity, D (m^{2}s^{-1})	7.45 10^{-10}

Table 1 Physical properties of the electrochemical solution at 25 °C

RESULTS AND DISCUSSION

Before undertaking unsteady flow measurements, a preliminary set of steady state measurements was carried out for Reynolds numbers of 32,000, 92,000 and 140,000 based on the inner pipe diameter d and on the centreline velocity. The velocity measurements were taken at a distance of 1.95 m from the inlet of the tube. The velocity profiles provided by Ultrasonic pulsed Doppler Velocimetry technique (UDV) were corrected in order to remove bias errors due to the crossing of media with different acoustic properties, ultrasonic field shapes, intensity spatial variability and the finite dimension of the sampling volume especially in areas close to the wall. The correction procedure suggested by Wunderlich and Brunn [16] was applied to the present data. The averaged velocity profiles were obtained from instantaneous measurements, during 100 s of acquisition. For each profile, the velocities were measured at 1024 points over a depth of 30.7 mm giving a 0,69 mm spatial resolution in the sound propagation direction. The time between two subsequent pulses was T_{PRF} = 53.69 ms. Measurements of flow parameters such as velocity profiles, pressure and wall shear stress, under unsteady flow conditions caused by rapid valve closure, were conducted. However, due to the lack of space, only a few representative results are reported here. The instantaneous velocity profiles and pressure were simultaneously collected. Since wall shear stress measurements required specific electrochemical solution, they were acquired later on thanks to the electromechanical valve that allows perfectly repeatable tests. Figure 2 shows the pressure waveform recorded by a pressure transducer and eight corresponding velocity profiles during the transient events. The velocities were obtained by time-averaging 75 velocity profiles. The transient event associated with Figure 2 has the following characteristics: the initial mean flow velocity is

2.42 m/s, and the valve is operated from a fully open to a fully closed position in 71 ms. The time history of the pressure and the velocities are measured at a 0.675 m distance upstream from the valve. The time origin, t=0, corresponds to the start of the manoeuvre of the valve. The points labelled with small numbers on the time history in the upper plot, label the instants corresponding to the velocity profiles displayed.

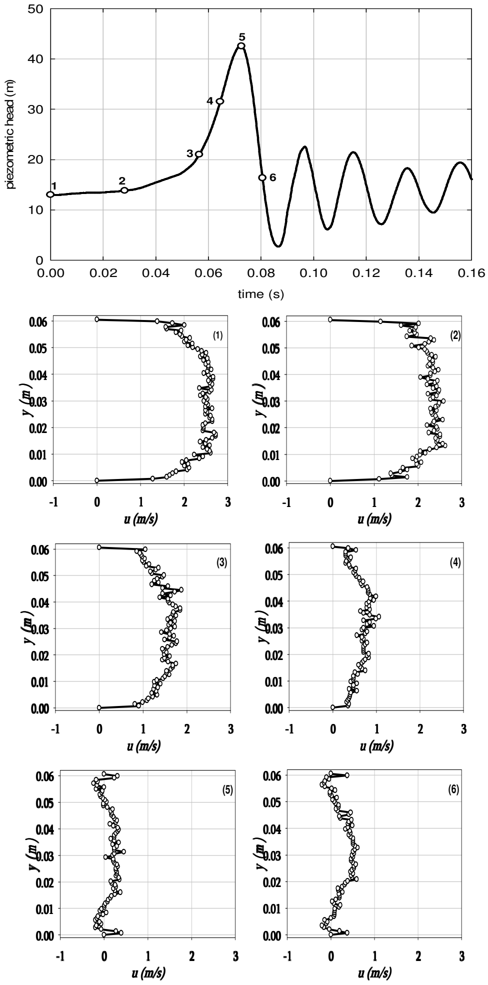

Figure 2 Experimental results showing pressure time history and associated velocity profiles

Figure 2 shows a pressure rise followed by damped pressure oscillations. The wave resulting from sudden compression of the fluid column near the valve propagates towards the inlet direction, reaches the free water surface in the tank and reflects back leading to observed oscillations. The waves dissipate and pressure at the measuring site restored to the steady-state value. The pressure wave celerity was calculated from the recorded data based on the analysis in the time and frequency domain of the pressure waveform. The mean value of this quantity was amounted to about a = 500 m/s. This mean pressure wave speed is also calculated from the following analytical solution:

$$a = \frac{\sqrt{K_w / \rho_p}}{\sqrt{1 + (1 - \nu_p{}^2)\frac{K_w}{E}\frac{D}{e}}} \qquad (7)$$

Where K_w, ν_p, ρ_p, E, e are bulk modulus, Poisson coefficient, mass density, Young's modulus, pipe-wall thickness, respectively.Equation (7) gives a pressure wave celerity value of 496 m/s, in a good agreement with that found experimentally.

The velocity profiles confirm the complex features of the flow field as it was suggested by Brunone et al [1]. During transient flows the instantaneous velocity profiles deviate significantly from the corresponding steady-state as shown in Figure (2). Moreover, the location of maximum velocity shifts out of the axis of the pipe and the point of maximum velocity moves during the transient event. A reverse flow occurs within a near wall annulus corresponding to 0.1< y/R< 0.2 (Figure 2 (5) and (6)) and may be interpreted by the so called annular effect that is different from that usually found in previous studies, characterized by negative shear stresses at the wall. For this particular event, it can be found that the mean velocity is approximately null while the velocity gradient near the wall is substantial. In other words, in such a condition, even with a significant wall shear stress, steady or quasi-steady criteria would give a null friction term.

Time dependence of the sectional mean velocity is shown in Figure 3. The mean velocity exhibits several phases. It decreases slowly from 0 to 0.04 s and undergoes a steep decrease in the time range from 0.05 to 0.07 s. The minimum mean velocity corresponding to the highest pressure peak, results from the reflected wave from the valve. A slight increase of the instantaneous mean velocity occurring at about 0.085 s is strictly linked to the minimum pressure value.

The instantaneous acceleration is shown in Figure 4. The acceleration is negative throughout the transient event except in the 0.075<t<0.085 time range corresponding to a steep decrease in the pressure. The present values of the acceleration range from 0 to -100 ms^{-2}, much higher values indeed if compared to those found in literature [2,3,6].

The unsteady wall shear stress derived from the Levêque solution is compared with that corrected with the inverse and Sobolik's methods. The wall shear stress is normalized with that obtained at t=0 at the beginning of the transient flow. It is clear from Figure 5 that the probe inertia correction is necessary, especially in the part of the transient event where the shear rate variation is significant.

Figure 5 shows that the Sobolik method gives nearly the same instantaneous wall shear rate as that given by the inverse method. For this particular unsteady flow, this method is quite suitable as compared with the inverse method, because no additional parameters are required and no initial guess of the wall shear stress is needed.

The wall shear stress is normalized with that obtained at t=0 at the beginning of the transient event, removing therefore uncertainties due to the difficulty to estimate the actual probe surface. In the same figure, the absolute pressure and the normalized wall shear stress predicted by using a quasi-steady assumption are displayed.

Figure 6 shows the wall shear stress measured with the electrochemical signals and that computed by a quasi-steady model from the velocity profiles are close for the time range between t = 0 s, corresponding to the start of the valve closure, up to t = 0.055 s. The present results differ from those of Shuy who found that the unsteady wall shear stress is higher than the quasi-steady values (computed from the Karman-Nikuradse equation based on instantaneous velocity), for a value of the acceleration parameter $\phi = \frac{2D}{\lambda_s V^2}\left|\frac{dV}{dt}\right|$ greater than 0.3.

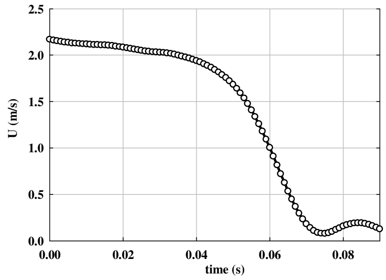

Figure 3 mean velocity during deceleration

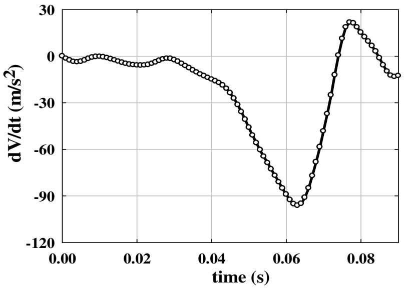

Figure 4 Instantaneous deceleration

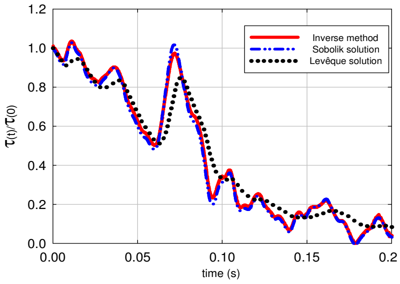

Figure 5 wall shear stress distribution calculated with different methods

For 0.06 s < t < 0.07 s, the quasi-steady assumption is no longer valid to determine the wall shear stress. The effective wall velocity gradient is considerably higher than the one resulting from the pseudo-steady approach. The unsteady wall shear stress inferred from the electrochemical probe increases up to a maximum value corresponding to that of the pressure. It is shown that the maximum unsteady wall shear stress value reaches the steady one at the end of this phase.

For t > 0.07 s, the unsteady wall shear stress tends asymptotically towards zero with large oscillations resulting from all reflected pressure waves.

Figure 7 gives a synthesis of the results of both unsteady wall shear stress component and acceleration (τ_{wu}).

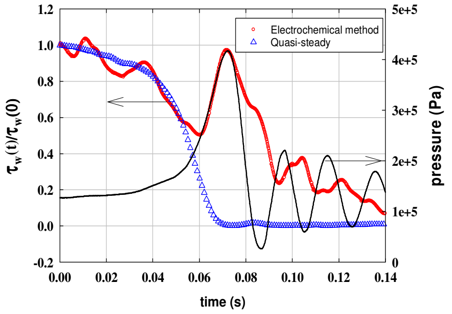

Figure 6 Wall shear stress and pressure distributions during a decelerating event

The values of the acceleration parameter of the present study range within $0 \leq \phi \leq 100$ for t < 0.05 s. Even for such high acceleration parameter, the present results show that the quasi-steady approach is still valid on the average. The ability of the electrochemical method to sense the local instantaneous flow unsteadiness is clearly shown in figure 6. Indeed, the wall shear stress exhibits a wavy behaviour probably due to the pressure wave originating from the valve closure. As for the quasi-steady model, it tends to smoothen out the actual wall shear stress fluctuations.

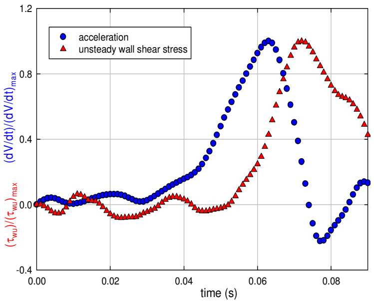

Figure 7 unsteady Wall shear stress component and acceleration

According to equation (3), it is expected that the changes in the unsteady wall shear stress component τ_{wu} correspond closely to those of the acceleration. It is shown that the sudden change in the core of the pipe, first affects the acceleration before unsteady wall shear stress is changed. As a result, changes in the velocity field of the fluid adjacent to the pipe wall, and in resulting wall shear stresses, lag behind flow rate changes in the core of the pipe. This should explain the discrepancies in phase shift between experimental and numerical head traces obtained in some previous studies with the friction model based on instantaneous local acceleration for later time of the transient flows.

Axworthy *et a*l [18] show that the empirical coefficient of unsteady friction is generally variable with space and time. They suggest that the unsteady friction formulae based on instantaneous accelerations such as Equation (3) are applicable to transient flow problems in which the wave passage timescale (L/a = 0.0052 s in the present study) is significantly shorter than the vorticity diffusion timescale ($\sqrt{2}\,D/2u_\tau=0.46$ s in the present study). According to Axworthy et al, the changes in wall shear stress in the conditions mentioned above, should correspond closely to the acceleration. In the light of the present study, it can be stated that the time scale arguments do not allow any definitive conclusion to be made to clarify the applicability of the instantaneous-acceleration approach in both attenuation and phase shift of the transient wall shear rate.

CONCLUSION

The electrochemical technique is combined with Ultrasonic pulsed Doppler Velocimetry for measurements of the unsteady transient wall shear stress and velocity profiles. during transient events the velocity profiles clearly show areas of reverse flows associated with increased velocity gradients at the wall. Acquired unsteady wall shear stress by using the electrochemical method provides complementary and additional near wall information to the velocity profiles and demonstrates the complex nature of the near wall flow field.

The present results show that the quasi-steady model for predicting the wall shear stress is valid for a wide ranging acceleration parameter and that the unsteady friction coefficient is unlikely to be constant for a non uniform decelerating flow. In the light of this study, the electrochemical method seems to be the most appropriate technique that could contribute to a better understanding of transient flow dynamics and energy dissipation. Further experimental measurements based on the electrochemical method should be performed in a longer pipe allowing both short and long time scales.

REFERENCES

[1] Brunone B, Golia U.M. and Greco M; Some remarks on the momentum equation for transients., *Int. Meeting on Hydraulic Transients with Column Separation, 9th Round Table, IAHR, Valencia, Spain,* 1991,pp.140-148

[2] Daily J.W., Hankey W.L., Olive R.W, Jordan J.M.; Resistance coefficient for accelerated and decelerated flows through smooth tubes and orifices; *Transactions of ASME*, 78, 1956, pp.1071-1077

[3] Shuy, E.B, Wall shear stress in accelerating and decelerating turbulent pipe flows., *Journal of Hydraulic Research, IAHR,* 34(2), 1996, pp.173-183

[4] Vardy A., and Brown J.M.B Discussion on wall shear stress in accelerating and decelerating pipe flows; *Journal of Hydraulic Research, IAHR*, 35(1), 1997, pp.137-139

[5] Cocchi G.; Esperimento sulla resistenza al deflusso con moto vario in un tubo; *Atti della Accademia delle Scienze dell'Instituto di Bologna*, 1989, pp.203-210.

[6] Kurokawa J., and Morikawa M.; accelerated and decelerated flows in a circular pipe *(First Report, velocity profile and friction coefficient); Bulletin of JSME*, 29 (249), 1986, pp.758-765.

[7] Hanratty T.J.; Campbell J. A.: Measurement of wall shear stress. *Fluid Mechanics Measurements (ed. Goldstein.) Washington, Hemisphere*, 1983 pp. 559-615

[8] Reiss L.P., and Hanratty T.J An experimental study of the unsteady nature of the viscous sub-layer, *AIChE J.9*, 1963, 154-160.

[9]. Sobolik V.; Wein O.; Cermac J.: Simultaneous measurement of the film thickness and wall shear stress in wavy flow of non-newtonian liquids. *Collect Czech Chem. Commun.*;52; 1987913-928

[10] Mao Z., Hanratty T.J, Analysis of wall shear stress probes in large amplitude unsteady flows, *Int. J. Heat Mass Transfer* 34, 1991, pp. 281-290.

[11] Rehimi F., Aloui F., Ben Nasrallah S., Doubliez L., Legrand J., Inverse method for electrodiffusional diagnostic of flows, *Int. J. Heat Mass Transfer* 49, 2006, pp. 1242-1254.

[12]Zidouh H., Etude expérimentale du frottement pariétal instationnaire, *Ph.D. Thesis, Université de Valenciennes*, France, 2007.

[13] Takeda Y., Velocity profile measurements by Ultrasonic Doppler Method, *Exp. Ther. Fluid Sc.* 10, 1995, pp. 444-453

[14] Berni A., Unsteady velocity profiles and energy dissipation in turbulent pipe flow, *PhD Thesis Dipartimento di Ingegneria Civile ed Ambientale, Perugia, Italy*, 2005.

[15] Nowak M., Wall shear stress measurement in a turbulent pipe flow using ultrasound Doppler velocimetry; *Experiments in Fluids* 33, 2002, p. 249-255

[16] Wunderlich T., and Brunn P.O A wall layer correction for ultrasound measurements in tube flow: comparison between theory and experiments, *Flow Meas. and Instr.*, 11, 2000, pp. 63-69.

[17] Vardy A.E., Brown J.M.B., Transient turbulent friction in fully rough pipe flows, *journal of Sound and Vibration* 270, 2004, pp. 233-257

[18] Axworthy, D. H., Ghidaoui M. S., McInnis D. A., Extented thermodynamics derivation of energy dissipation in unsteady pipe flow, J. Hydr. Engrg., ASCE, 126 (4), 2000, 276-287.