PIV characterization of transient flow in pipe coils
Moisés Brito, Pedro Sanches, Rui M. Ferreira, Dídia I. C. Covas

Abstract

A comprehensive knowledge of velocity profiles and wall shear stress during the accelerations and decelerations of the flow is essential to understand the dissipation mechanisms in transient flows and to develop adequate mathematical models. Currently, most one-dimensional transient solvers are not accurate enough to describe the physical behavior observed, tending to underestimate observed momentum dissipation in fast transient events. This paper aims to contribute to a better understanding of water hammer flow dynamics by measuring the instantaneous velocities in pipe coils using Particle Image Velocimetry (PIV). Measurements were carried at a middle section of a coiled copper pipe with 103.2 m of length, 20 mm of nominal diameter, 1 mm of pipe-wall thickness and 1 m of the coil diameter. Measured velocity profiles for steady state flows are asymmetrical in the pipe cross section (unlike in straight pipes), with higher velocities in the outer region due to the centrifugal force created by the flow in the coil. Velocity profiles during transient flows have clearly shown regions of flow recirculation and a large flow reversal near the pipe wall, occurring first in the inner side of the pipe cross-section as a result of the profile asymmetry. Transient shear stress in lower than the one from the initial steady state, showing that this parameter cannot describe per si the momentum dissipation in transient events.

Keywords: PIV; water hammer; velocity profiles; wall shear stress.

1. Introduction

The velocity profiles measurements in pipes have been carried out by different authors and using different instrumentation [1,2,3,4,5]. These profiles present well-defined characteristics under laminar and turbulent regime...
for steady state flows; however, in unsteady flows, the velocity profiles inverted due to acceleration and deceleration of the flow as observed experimentally. Velocity profiles have been measured during transient events using a laser velocimeter [2] and an Acoustic Doppler Velocity Profiler [3,6,7]. While slow transients behaved in a quasi-steady state manner, fast transients deviated significantly particularly next to the wall; in decelerating flows, the velocity close to the wall has an opposite direction of the one in the pipe axis (“annular effect”), causing steep velocity gradients. These gradients that are very important for the calculation of friction are very difficult to accurately measure very close to the wall, requiring very precise equipment (e.g., PIV). Results clearly demonstrate the complex nature of the transitions between flow states and the range of fluid behavior that will ultimately need to be taken into account in comprehensive numerical models. This effect also generates major changes in the wall shear stress, demonstrating the underestimation of unsteady friction losses by the numerical models [7,8,9,10,11,12].

Unsteady-friction losses have been widely studied, as these losses are particularly relevant in fast transients or high-oscillating frequencies. While analytical solutions have been derived for unsteady friction in laminar flows [13,14], no universal formula exists yet for turbulent flows. Flow instabilities change the structure and strength of the turbulence in a pipe, result in strong flow asymmetry, and induce significant fluctuations in wall shear stress. Although great progress in modelling dissipation in transient flow has been achieved, current models overlook instabilities and their effects on transient analysis. Several formulations have been proposed to estimate the unsteady wall shear stress in turbulent flows, as a function of: instantaneous mean velocity [15]; instantaneous acceleration [16]; weights of past time local accelerations [17]; local and convective accelerations [11,18,19]; and velocity profiles [20,21,22,23]. An excellent review paper on water hammer theory, including extensive discussions of the existing unsteady friction models, can be found in [24].

The current paper aims to measure the instantaneous velocities during transient flow carried out in a coiled copper pipe under controlled laboratory conditions. This paper includes the description of the experimental facility used and set of experimental tests carried out, a brief description of the PIV and the comparison of experimental and theoretical velocity profile for straight pipes. Finally, the main characteristics of transient velocity profiles and wall shear stress are discussed.

2. Data collection and processing

2.1. Experimental setup and instrumentation

An extensive experimental data collection was carried out in the pipe rig at the Laboratory of Hydraulics and Water Resources, in the Department of Civil Engineering, Architecture and Geo-resources of the Instituto Superior Técnico. The system is composed of a coiled copper pipe with approximately 103.2 m of length (L), 20 mm of inner diameter (d), 1 mm of pipe-wall thickness (ε) and 1 m of coil diameter (D). The system is supplied from a storage tank with 125 l by pump with nominal flow rate of Q=1 m³/h and nominal elevation of H=32 m. Immediately downstream of the pump there is a stainless steel hydro-pneumatic vessel with 60 l and designed for the nominal pressure of 6 bar. At the downstream end of the pipe there is a set of electro valve and globe valve that allow the generation of water hammer and control of the flow rate, respectively. The rig was assembled with a portable metal frame, 1 m wide, 2 m long and 1.2 m height. Fig. 1(a) shows a schematic of the experimental facility.

The facility is equipped with instrumentation for collecting steady and unsteady state flow data. Steady state flow rates are measured by a rotameter and transient pressures are measured by three strain-gauge type pressure transducers located in different sections of the pipe (x = 0, 50, 100 m) using a data acquisition system (Picoscope). The instantaneous flow velocities are measured by Particle Image Velocimetry (PIV) at the measurement section, located practically in the middle of pipe at a distance x = 43 m downstream the reservoir. The measurement section is made of Perspex tube with 0.1 m of length and 22 mm of inner diameter, allowing cross of the light sheet.

PIV is an indirect technique for measuring instantaneous flow velocities in planar regions of the flow. The PIV system allows obtaining the fluid velocity by measuring small displacement of seeding particles, illuminated by a laser sheet and recorded by a camera [25]. The system is composed of a laser head, a power supply, a generally pulsed, with its optics, a CCD camera, both synchronized and controlled by software, a timing unit, a frame grabber and processing software (Fig. 1b).
A 2D PIV system of 30 mJ/pulse Nd:YAG (Neodymium-doped Yttrium Aluminum garnet) with maximum sampling frequencies of 15 Hz is used. The laser beam has a green light with 532 nm of wavelength. The system is based on a double-cavity laser operated at user-defined time between pulses and sampling frequencies was 15 Hz and. PIV measurements require the introduction of seeding targets in the flow. The seeding particles used in this experimental work for flow visualization were made of polystyrene with nominal diameter of 13 µm. The acquisition and processing of data were made using the software DynamicStudio®. The synchronisation between the PIV system and electro valve (begin the water hammer) was performed using an external trigger connected the software DynamicStudio®. This trigger allows input the time delay between the start of electro valve (beginning of the water hammer) and PIV and data acquisition system.

2.2. Acquisition and processing data

The light sheet of PIV is oriented perpendicular to the main flow direction (Fig. 1b), allowing to measure the flow structures advected through the measurement plane by the mean flow. The local coordinates of measurement plane \( x \)- and \( y \)-axes are aligned by axial a transversal of Perspex tube, respectively. The velocity axial component, \( u \), and the transversal component, \( v \), is given by:

\[
\begin{align*}
  u(x, y) &= \frac{(x - \Delta d_x) - x}{\Delta t} \\
  v(x, y) &= \frac{(y - \Delta d_y) - y}{\Delta t}
\end{align*}
\]

where \( \Delta d_x \) and \( \Delta d_y \) are respectively the displacement axial and radial of seeding particles and \( \Delta t \) is the time between pulses. During these experimental tests, the PIV was operated at \( \Delta t = 500 \mu s \).

The measurements were carried out for a flow rate \( Q = 400 \text{ l/h} \) corresponding to the mean flow velocity in the copper \( U = 0.35 \text{ m/s} \) and Reynolds number \( \text{Re} \ (Ud/\nu) = 7073 \). The water mean temperature during the tests was 21º C, corresponding to a kinematic viscosity \( \nu = 10^{-6} \text{ m}^2/\text{s} \). The velocity flow field was measured for three time delays \( t_d = 0, 0.02 \) and 0.04 s, due to the small period of the pressures waves \((T = 4U/c = 0.35 \text{ s})\). This time delay allows to measure most points over the time history of piezometric head (Fig. 2). For each \( t_d \), 150 tests were carried out during a total acquisition time of 10 s. Each acquisition consisted of the collection of 15 images. The CCD camera used has a size of 1600×1200 px² and the image frame is interrogated in 16×16 pix² sub-images at intervals of 8 pix (i.e. a 50% overlap). Each image frame yields a data set of 199 rows of 149 columns. The corresponding width of the interrogation image in the flow is variable due to the cylinder shape. The algorithm based on adaptive correlation to determine instantaneous velocity vectors is used.
The correction of all interrogation images results in the maps of displacement vectors in units of CCD camera (px) making necessary to convert into the international system (SI) of units (m). The conversion was performed using the calibration factors \( F_x \) and \( F_y \), respectively, for axial and radial directions and \( \Delta d_x(m) = F_x \Delta d_x(\text{pix}) \) and \( \Delta d_y(m) = F_y \Delta d_y(\text{pix}) \). These factors correspond to the relation between a given distance in SI and CCD camera units determined by the calibration grid.

2.3. Calibration procedure

The calibration grid shown in Fig. 3 has been used to correct of the optical distortion due to the cylinder shape of the Perspex tube. The calibration relation is obtained acquiring images of a plane Perspex tube target with an equally spaced grid of black dots. The calibration grid has a zero marker diameter of 3.5 mm, axis marker diameter of 1.5 mm and the main marker diameter of 0.75 mm, and the space between the geometrical centers of the dots is 3 mm printed on a transparent sheet and glued between two 1.5 mm thick Perspex plates. Fig. 3 shows the warped picture of the calibration grid. A regular grid of black dots is superimposed on the warped calibration picture.

Fig. 3 shows that, in the pipe radial direction \( y \), there is a higher deformation of the dots, however, for axial direction \( x \) this deformation is practically null. The ideal mapping function would project all markers from the calibration picture into the position of the black dots [26]. The mapping function is defined by the 3\(^{rd}\) order polynomial function that will transform a point in the object space \((X\) and \(Y)\) into a point in the image plane \((x\) and \(y)\), described by formula below:

\[
\begin{bmatrix}
    x \\
    y
\end{bmatrix} = A_{000} + A_{100}X + A_{010}Y + A_{110}XY + A_{200}X^2 + A_{201}XY + A_{210}Y^2 + A_{300}X^3 + A_{310}X^2Y + A_{301}XY^2 + A_{312}XY^2
\]  
(2)

where \(A_{ijk}\) are the coefficients of polynomial function. The coefficients of the Direct Linear Transformer-parameters are also calculated. This is because inverse mapping (from image to object) requires iteration for solving of Eq. (2), and results from a corresponding inverse Direct Linear Transformer-mapping is used for the initial guess.
3. Results analysis and discussion

3.1. Steady velocity profile

The experimental and the theoretical steady time-averaged streamwise velocity profiles, \( u \), are presented in Fig. 4. The theoretical velocity profile in a straight pipe is estimate for \( y^+ > 30 \) by the logarithmic law of the wall [27]:

\[
u^+ = \frac{1}{\kappa} \ln(y^+) + 5.5
\]

where \( \kappa = 0.41 \) is the von Kármán constant for smooth wall pipes, \( u^+ \) is the dimensionless velocity, \( u^+ = u / u_* \), \( y^+ \) is the dimensionless wall coordinate, \( y^+ = (R - r)u_* / \nu \), and \( u_* \) is the friction velocity or shear velocity computed by wall shear stress, \( u_* = 0.019 \) m/s. The viscous and buffer sublayers, described by \( y^+ < 5 \) and \( 5 < y^+ < 30 \), are very thin and cannot be presented in Fig. 4.

Measured velocity profiles for steady state flows have shown a large asymmetry in the pipe cross section, being the velocity profile very different from that of straight pipes, with higher velocities in the outer region. This is due to the centrifugal force created by the flow in the coil. This effect is represented by a Dean number (i.e., ratio of the square root of the product by centrifugal inertial force and viscous force), which is in the current case \( Dn = 0 \). This parameter reflects the deformation of the velocity profile: the higher Dean number is, the higher the deformation of profile is. In straight pipes, the dean number is equal to zero.

![Fig. 4. Steady time-averaged streamwise velocity profile: experimental (black arrow) and theoretical (gray arrow)](image)

The steady time-averaged streamwise velocity field presented in Fig. 4 shows hardly no difference in the profiles along the axis of the pipe in the measurement window of 0.04 m. However, this difference is more significant in areas where there is inflection of the velocity profile (i.e., in the pipe axis).

Steady state velocity profiles were integrated by two methods to estimate the flow rate in the pipe and compared to the measured flow rate by the rotameter. The first method (Method I) calculated the mean velocity in the measured plane and obtained error was 10 \%. The second method (Method II) was assuming that the velocity profile was the same in half of the pipe and the error was 3\%. The latter was considered a good approximation.

3.2. Unsteady velocity profile

Velocity profiles measure during the transient event are depicted in Figure 6 from t=0 s until t=0.40 s (around one period of the pressure wave). The velocity profile at \( t = 0 \) s represents the beginning of water hammer and the velocity profile is equal to steady velocity profile. Velocity profiles during transient flows have clearly shown regions of flow recirculation and a large flow reversal near the pipe wall, occurring first in the inner side of the pipe cross-section as of result of the profile asymmetry, as shown in Fig. 5.
The dynamics of velocity profile is due to the fact that a pressure wave causes a constant piezometric head, $\Delta H$, throughout the cross section. The piezometric head can be evaluated by means of the Joukowsky equation:

$$\Delta H = \frac{a\Delta U}{g}$$ \hspace{1cm} (4)

where $\rho$ is the water density, $g$ is the gravitational acceleration, $a$ is the wave speed and $\Delta U$ is the mean velocity change obtained by integrating the instantaneous velocity profiles.

The time history of piezometric head obtained by integrating the instantaneous velocity profiles and measured by pressure transducers located in section $x = 50$ m are presented in Fig. 6. These results show a good agreement between the piezometric head, however the measured head by the pressure transducers is higher than the one obtained by integrating the instantaneous velocity profiles. This difference is partially caused by the asymmetry of the profile along the radial direction and the integration method and partially due to the distance between the PIV and the transducer measurement sections (about 6 m).

### 3.3. Transient wall shear stress

The mean velocity variation calculated by the integration of the measured velocity profile using Method II (as explained in section 3.2) and the wall shear stress variation along time (calculated using steady state formulas as a function of mean velocity, $\tau = \gamma R_0 J$; $J = f U^2 / 2 g D$; $f = 0.3165 \text{Re}^{-0.25}$) are presented in Fig. 8. The transient
wall shear stress increases during the acceleration phase and decreases in the deceleration phase. Despite the observed pressure damping being higher during the transient event than in steady state, the wall shear stress is lower during the transient event than during the initial steady state flow; this means that momentum dissipation during the transient event cannot be exclusively described by this parameter but also by the turbulence of the flow created by the inversion of the velocity profile.

\[
\tau^* (Pa) = \frac{U_m}{s} \cdot \frac{1}{U_m}
\]


4. Conclusions

In this paper water hammer dynamics in turbulent regime is analysed at by means of instantaneous velocity profile measured by a PIV in a long coiled copper pipe. In the first part of the paper, experimental steady velocity profiles are analyzed by comparison with theoretical profile with the theoretical one for a straight pipe. Measured velocity profiles for steady state flows are asymmetrical in the pipe cross section (unlike in straight pipes), with higher velocities in the outer region due to the centrifugal force created by the flow in the coil. Velocity profiles during transient flows have clearly shown regions of flow recirculation and a large flow reversal near the pipe wall, occurring first in the inner side of the pipe cross-section as of result of the profile asymmetry. The quantitative comparisons between time history of piezometric head obtained by integrating the instantaneous velocity profiles and measured by pressure transducers located in section \( x = 50 \text{ m} \) showed a good agreement between the piezometric head. Transient shear stress in lower than the one from the initial steady state flow, showing that this parameter cannot per si describe the momentum dissipation in transient events.

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