Pressure and velocity variation of unsteady flow in pipes

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Abstract
Valve closure in a system of piping creates high and low pressure waves which travel along the system and decay as a result of wall shear stress. Comparison of experimental and theoretical results revealed the failure of steady or quasi-steady models in correctly predicting the damping process of the pressure waves. The aims of this paper are to increase the number of available velocity profiles and to give a contribution to the understanding of transient flow dynamics. With this purpose, experimental measurements by Ultrasonic Pulsed Doppler Velocimetry of the velocity field for water hammer transients in a long polyethylene pipe, caused by a downstream sudden valve closure. Velocity data are analyzed and compare with results obtained by other authors.

Keywords: Water hammer, Transient flow, Ultrasonic Doppler, Velocity Profile.

1. Introduction
The pressure developed in a piping system as results a sudden velocity change transmitted in the pipe at a certain velocity that is determined by fluid properties and the pipe wall material. This phenomenon, called water hammer, can cause pipe and fittings rupture. The intermediate stage flow, when the flow conditions are changed from one steady state condition to another steady state, is called transient state flow or transient flow; water hammer is a transient condition caused by sudden changes in flow velocity or pressure. When performing load data analysis on water hammers, it is a common practice to make a number of conservative assumptions. This could result in a great overestimation of the actual loads, which could lead to an exaggerated overcompensation. This may lead to an increase in the use of pipe supports, yielding a very stiff system of pipes that could be less resistant to other loads that are apparent. One major reason to the overrating of water hammer loads is the common use of the quasi steady friction model when simulating transient pipe flow. This model is very simple and is derived from steady state friction analysis for laminar as well as turbulent pipe flow. (See equation (1))

\[ \tau_{\text{wh}}(t) = \frac{\rho f(t)V(t)V'(t)}{8} \]  

(1)
Where \( \tau_{ws}(t) \) = quasi-steady wall shear as a function of time (t).

In other words, the quasi-steady approach assumes the friction factor to be dependent on the mean velocity, local and actual Reynolds number.

The application of such a simplified wall shear stress model to unsteady problems is satisfactory only for very slow transients, in which the shape of instantaneous velocity profiles does not differ markedly from the corresponding steady-state ones. During fast transients, velocity profiles change in particular and more complex manners (Brunone et al. 2000b), showing greater gradients, and hence greater shear stresses, than the corresponding steady flow values. During these fast transients, the quasi-steady approach is not valid as it underestimates the friction forces and overestimates the persistence of oscillations following the first one, leading to discrepancies between numerical results and experimental data (e.g., Eichinger and Lein 1992, Brunone et al. 2000b, Bergant et al. 2001).

The aims of this work are to achieve a number of unsteady velocity profiles and to give a contribution to the understanding of transient flow dynamics. With this purpose, experimental measurements by Ultrasonic pulsed Doppler Velocimetry of the unsteady velocity field for water hammer transients in a long polyethylene pipe, caused by a downstream sudden valve closure, are presented. Velocity data are quality analyzed and compared with results obtained by other authors.

Measuring the velocity profiles in closed conduits has always represented an interesting field in Hydraulics. The approach to study this subject has changed with time, depending on practical interests, measuring and computational capabilities. The availability of high frequency local velocity probes has permitted to acquire unsteady velocity profiles in the last few decades. Hino et al. (1976) by hot-wire anemometry, Das and Arakeri (1998) by hot-film anemometry, Lefebvre and White (1989) and Greenblatt and Moss (2003) by Laser Doppler Velocimetry (LDV), principally interested in the transitions in turbulence, deserve to be mentioned. Moreover, by means of LDV, some particular characteristics of unsteady velocity distributions have been published by Van de Sande et al. (1980) and Jönsson (1991), for accelerated and decelerated flows, respectively.

The application of hot wire/film or Laser Doppler anemometry is time consuming and difficult as they provide single-point measurements. This aspect requires the exact repetition of each test for a number of times equal to the number of desired points in each velocity profile. This practical difficulty can be overcome by adopting an Ultrasonic pulsed Doppler Velocimeter (UDV), as it provides the entire instantaneous velocity profile, even if at lower sampling frequencies (tens of Hertz) and with a single component (Willemetz, 2000).

2. Materials and Methods

The experimental survey presented in this paper were performed at the “Hydraulics Laboratory, Faculty of Water Sciences Engineering” of the University of Shahid Chamran, Ahwaz, Iran. It is made up of some systems: a supply and recycling system, a data acquisition apparatus and, finally, the main experimental installation composed of the high density polyethylene pipe and the downstream electromechanical valve. The main experimental apparatus is composed of a high density polyethylene pipe, HDPE, 80 m long, with an inner diameter of 53.6 mm and a thickness of 4.7 mm. The pipe is arranged in concentric circles with bends having a minimum radius of 1.5 m and is almost horizontal, except for the last short part. At the end of the pipe a butterfly electromechanical valve discharges into a free surface tank. The fluid used was water, and constant total head and temperature were maintained.

2.1 Experimental procedure

A DOP-2000 ultrasonic pulsed Doppler velocimeter manufactured by Signal Processing (Lausanne,
Switzerland) was used for the measurements. This instrument is able to perform instantaneous measurements of velocity at a number of points (up to 114) of a properly seeded fluid flow, along the direction of emission of the ultrasonic signal, with remarkably high resolutions in space and time. It is therefore an interesting tool for turbulent flow analysis, where high spatial and temporal accuracies are required for both instantaneous measurements and averaging operations.

Before undertaking unsteady flow measurements, a field which lacks in experimental data, the accuracy of the experimental apparatus had to be verified. With this aim, a preliminary set of steady state measurements was carried out, and the results compared with some well-known references in literature. These comparisons were necessary to focus problems and find solutions, leading to an effective final experimental setup. Moreover, comparisons disclosed the need of data correction techniques, to verify the effect of implemented procedures. As a reference, data collected by Nikuradse (1932, Pitot probe) and Laufer (1953, hot wire), carried out in smooth pipes and similar Reynolds numbers, were chosen.

Ultrasonic probe positioning: In order to correctly and easily impose the ultrasonic probe inclination, a rigid system with a sole degree of freedom, permitting a 180° rotation of the transducer, was designed; such a device keeps the probe aligned with pipe axis. The ultrasonic field continuity between the probe and the pipe wall was assessed immersing the whole measuring section in water (the same as the flowing fluid) by means of a specific waterproof housing.

Data correction procedure: Data provided by UDV technique must be corrected for the following reasons: crossing of media with different acoustic properties, ultrasonic field shape and intensity spatial variability, finite dimension of sampling volume. Hence, the correction procedure by Wunderlich and Brunn (2000) was implemented, based on geometrical considerations and made of two different phases.

The first phase concerns echoes repositioning due to the crossing of two interfaces, namely “coupling fluid – wall” and “wall – flow”. This correction is based on the simplifying hypothesis of plane interface and linear ultrasonic beam and modifies every point of the profile (Figure 1). The second phase concerns the correction of data close to the wall. Local velocity measurements are located in sampling volume’s centroid (cylinder ABCD in Figure 1): if such a volume is located partly within the pipe and partly within the flow, the local velocity measurement must be shifted to the centroid of the actual sampling volume, i.e. the portion volume within the flow (AHKD in Figure 1). This second correction only modifies some points of the profile (Brunone et al.2000b).

### 2.2 Measurements

Tests were carried out in the “Hydraulics Laboratory, Faculty of Water Sciences Engineering of the University of Shahid Chamran, Ahwaz, Iran” and were includes of the simultaneous measurements of the following quantities:

1. Discharge in the pipe line by flow meter UF 5000.
2. water temperature
3. Dynamic pressure at 6 point located in the pipe line.
4. Differential pressure in a portion of pipe 4 m in length, which includes the velocity measuring section.
5. Measuring velocity profiles by DOP2000

Before measuring velocity profiles it was necessary to test pressure constancy in the model reservoir. During all acquisitions, the maximum pressure variability inside the reservoir was equal to ± 10cm.
3. Results and Discussions

According to raw data have been achieving by the DOP 2000 with MATLAB software operation was performed under the direction of correction:

1- Mean velocity profiles were calculated.
3- Comparison with non-dimensional Nikuradse and Laufer profiles in the plane \( \left( \frac{u}{U_{\text{ref}}}, \frac{y}{r} \right) \).

The data correction procedure, applied to a mean velocity profile characterized by a Reynolds number \( \text{Re} = 58000 \), provides the result shown in Figure 2. The average profile was obtained from instantaneous measurements, during 100 s of acquisition.

Figure 2 clearly demonstrates velocimeter difficulty in correctly measuring local velocities close to the opposite wall. Indicating with \( y \) the distance from the wall perpendicular to flow direction (\( y/r = 0 \) indicates the wall, \( y/r = 1 \) the pipe axis), it was observed that for \( y/r > 0.03 \) the percentage of observations increases to 50%, reaching values of 60-65% for \( y/r > 0.04 \). The number of observations decreases close to the wall for two reasons: low velocities, with consequential difficulty of particles to trace the flow, and reduced dimension of effective sampling volume (Figure 1). For these reasons, velocities measured in \( y/r < 0.03 \) (corresponding to \( y = 0.78 \text{mm} \), similar to longitudinal sampling volume’s dimension), show a greater uncertainty. Velocity measurements with \( y/r < 0.03 \), even if less reliable, have not been discarded because of their importance in estimating the wall velocity gradient, in steady and unsteady flow conditions. (The chosen part was that close to the probe) Figure 3 shows measured steady velocity profiles, with Reynolds numbers between 7440 and 60500 (Figure 3). Because similar results have been obtained for different Reynolds number flow, here only the details of the one of the executed test are presented. Figure 4 shows the comparison among raw data, corrected velocity profiles and Nikuradse and Laufer measurements, for similar Reynolds numbers. In Figure 4, \( u_{\text{max}} \) refers to the maximum velocity observed in the pipe axis. Standard deviation is defined as the relation:

\[
DI = \left( \frac{u_{\text{m}} - u_I}{u_I} \right) (100)
\]

Where \( u_{\text{m}} \) is the local measured velocity and \( u_I \) the reference value (provided by other authors). Therefore, it is possible to evaluate in quantitative terms the effect of the data correction procedure which was implemented (Figure 5).

Figure 5 shows the deviation computed from data reported in Figure 4 it is evident how the data correction technique considerably reduces \( DI \) which passes from maximum values of about 25–30% to 6%.

Significant importance of data correction techniques, reducing the standard deviation between the results of the UDV and reference data (Nikuradse and Laufer) in the area is near the wall. It is very important to estimate the wall shear stress in transient flow.

4. Conclusions

In the past, most velocity measurements in transient flow were carried out by means of hot wire and Laser Doppler Velocimetry. In this study, Ultrasound Doppler Velocimetry (UDV) was preferred to other techniques. The main aims of this study providing experimental data by means of UDV during water hammer experiment. Data provided by UDV technique had to be corrected (implementing the correction procedure proposed by Wunderlich and Brunn (2000).) for the following reasons: crossing
of media with different acoustic properties, ultrasonic field shape and intensity spatial variability, finite dimension of sampling volume. The corrected data of steady state measurements were in good agreement with the previously reported data of Nikuradse (19932), Laufer (1953).

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References
Figures

Figure 1. Data correction procedure
Figure 2. Data correction proposed by Wunderlich and Brunn (2000)
Figure 3. Steady velocity profiles with Re in the range of 7440-60500
Figure 4. Non-dimensional \( \left( \frac{u}{u_{max}}, \frac{y}{r} \right) \) comparison among raw data, corrected measures and Nikuradse (1932) and Laufer (1953) profiles for similar Re
Figure 5. Standard deviation related to the non-dimensional \( \left( \frac{u}{u_{\text{max}}} \cdot \frac{Y}{r} \right) \) comparison among raw data, corrected measures and Nikuradse (1932) and Laufer (1953) profiles for similar Re.