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Optimisation of Pulsed Ultrasonic Velocimetry system and transducer technology for industrial applications

Reinhardt Kotzé [a,*], Johan Wiklund [b], Rainer Haldenwang [a]

[a] FPRC – Flow Process Research Centre, Cape Peninsula University of Technology, PO Box 652, Cape Town 8000, South Africa
[b] SIK – The Swedish Institute for Food and Biotechnology, Göteborg, Sweden

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ABSTRACT

Pulsed Ultrasonic Velocimetry, commonly referred to as Ultrasonic Velocity Profiling (UVP) in research and engineering applications, is both a method and a device to measure an instantaneous one-dimensional velocity profile in opaque fluids along a measurement axis by using Doppler echography. Studies have suggested that the accuracy of the measured velocity gradient close to wall interfaces need to be improved. The reason for this is due to distortion caused by cavities situated in front of ultrasonic transducers, measurement volumes overlapping wall interfaces, refraction of the ultrasonic wave as well as sound velocity variations (Doppler angle changes). In order to increase the accuracy of velocity data close to wall interfaces and solve previous problems a specially designed delay line transducer was acoustically characterised and evaluated. Velocity profiles measured using the delay line transducer, were initially distorted due to the effect of finite sample volume characteristics and propagation through the delay line material boundary layers. These negative effects were overcome by measuring physical properties of the ultrasonic beam and implementing a newly developed deconvolution procedure. Furthermore, custom velocity estimation algorithms were developed, which improved the time resolution and penetration depth of the UVP system. The optimised UVP system was evaluated and compared to standard transducers in three different straight pipes (inner diameters of 16, 22.5 and 52.8 mm). Velocity data obtained using the optimised UVP system showed significant improvement close to wall interfaces where the velocity gradients are high. The new transducer technology and signal processing techniques reduced previously mentioned problems and are now more suitable for industrial process monitoring and control.

1. Introduction

UVP is both a method and a device to measure an instantaneous unidimensional (1D) velocity profile along a measurement axis by detecting the Doppler shift frequency information echoed by particles contained in the fluid as a function of time [1–4]. This technique is ideal since it is non-invasive, works with opaque systems, inexpensive, portable, and easy to implement relative to other velocity profile measurement methods [5–7]. UVP is accepted as an important tool for measuring flow profiles in opaque liquids in research and engineering [8]. UVP has also been combined with simultaneous pressure drop measurements (PD) to allow determination of rheology in-line. The new tube viscometer concept is commonly referred to as the UVP-PD method and has been successfully applied to a wide range of fluid systems, including a range of model and industrial fluids and suspensions, containing both soft and hard particles and fibres with diameters from a few nanometers up to several centimetres in length, see [9]. It has been evaluated for several potential industrial applications, such as; polymer melt rheology by Dogan et al. [10], paper pulp by Wiklund et al. [11] and Fock et al. [12], concentrated mineral suspensions by Kotze et al. [13], fat crystallisation by Birkhofer et al. [14], Young et al. [15] and Wassel et al. [16]. However, there are still a few problems remaining with the UVP instrumentation and methodology in order to achieve the robustness and accuracy required in industrial applications. One major problem is that all existing transducers and instrumentation are not designed for measurements inside small and complex geometries, such as industrial processing pipes. Also, the UVP technique has been adapted from designs and methodologies found in the medical industry for measurement of blood flow. However, human blood is not very attenuating compared to current industrial fluid systems and thus the existing UVP transducers and instruments are not able to provide acoustic pulses that can penetrate across large pipe diameters, which is commonly found in industrial applications. At the same time, the shape of the beam/pulse (measuring volume) should be preserved, with high and constant acoustic pressure, over a fixed distance along the measuring axis in order to allow accurate measurements.

* Corresponding author.
E-mail address: reinhardtkotze@yahoo.com (R. Kotzé).

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Nomenclature

A	total area (m^2)
d	distance along contraction length (m)
D	pipe inner diameter (m)
f_d	Doppler frequency (Hz)
f_e	emitted Doppler frequency
$\hat{f}$	Fourier transform of Doppler signal, dimensionless
I	in-phase echo data, dimensionless
I	sample volume intensity (V)
K	fluid consistency index (Pa s^n)
L	unit length (m)
n	flow behaviour index, dimensionless
n	(subscript) segment number, dimensionless
N	total number of segments, dimensionless
ΔP	pressure drop (Pa)
Q	quadrature-phase echo data, dimensionless
Q	volumetric flow rate (l/s)
r	radial position (m)
R	pipe radius (m)
R_{e2}	Reynolds number, dimensionless
R_{plug}	Plug radius (m)
S	power spectrum, dimensionless
t	time-of-flight (s)
v	velocity (m/s)
V	bulk velocity (m/s)
V_m	measured velocity profile (m/s)
V_t	true velocity profile (m/s)
w	angular frequency Ra/s
Greek letters	
$\dot{\gamma}$	shear rate (Pa s^{-1})
θ	Doppler angle (°)
τ	shear stress (Pa)
τ_y	yield stress (Pa)

Due to the current transducer designs, the pressure field produced by the ultrasonic transducer is highly irregular from the transducer's surface and extending all the way up to the focal point. This distance is usually quite long (typically around 17 mm for a 4 MHz transducer in water) and is known as the near-field distance [17]. Accurate velocity measurements are not possible in this region, which makes the transducer installation complicated and this has therefore limited the practical applicability of the UVP method for industrial applications. To overcome this problem, simple flow adapter designs for transducer housings have been used that enable the transducer surface to be in direct contact with the test fluid, thus ensuring maximum ultrasonic energy transfer into the fluid system as well as eliminating any beam refraction. However, this setup leaves a cavity before the wall interface which causes measurement uncertainty due to fluid flow and increased velocities beyond the actual pipe wall (see Fig. 1).

Furthermore, when measuring in more complex, industrial fluids, problems of particle sedimentation inside the cavities cause velocity of sound and Doppler angle variations, which can distort the measured profile significantly [4,13]. More consequences of particle build-up and density changes inside cavities are the negative effects of temperature and fluid concentration gradients. This also causes velocity of sound variations and it has been shown that temperature gradients can cause errors in velocity profile estimation across the measurement line [18].

It is possible to measure through solid material layers and pull back the transducer from the liquid–wall interface, thus eliminating both the cavity and the near-field problem. However, ultrasonic beam refraction and absorption causes errors in parameters such as the Doppler angle and sound speed, and this significantly reduces the penetration depth in attenuating fluids. It has been shown by Messer and Aidun [19] that the physical ultrasonic beam shape changes when measuring through material layers. If the acoustic properties of the pulses emitted and received by the transducer change, for example due to propagation through solid interfaces, more errors due to increased sample volume dimensions (widening of ultrasonic beam) are introduced into the velocity measurement, which leads to inaccurate results especially within the near-wall region which is of highest interest. Several methods for correcting the measured velocities in the near-wall region have been proposed, but with limited success [20,21].

Apart from the transducer design and installation difficulties, current commercial UVP instruments are only capable of estimating velocities across the ultrasonic beam axis using only one algorithm, usually integrated in the Digital Signal Processor (DSP), which limits the overall control for more accurate measurements. Existing systems also employ simple and standard filters for noise reduction caused by low signal-to-noise ratios or other artifacts during measurements, which result in noisy data and erroneous velocity estimations.

The main objective of this research work was to optimise the UVP system for accurate complex flow measurements by evaluating a specially designed delay line transducer and implementing advanced signal processing techniques. Results were compared with that obtained using the existing standard UVP system as well as using the new delay line transducer combined with new software.

2. Theory

2.1. Velocity profile model

The equation for the Herschel–Bulkley model is as follows:

$$\tau = \tau_y + K(\dot{\gamma})^n, \tag{1}$$

where K, n and τ_y are three empirical curve-fitting parameters [22]. Eq. (1) can be integrated to give the velocity (v) profile across the pipe radius:

$$v = \left(\frac{n}{(1+n)}\right)\left(\frac{\Delta P}{2LK}\right)^{\frac{1}{n}}\left((R-R_{plug})^{1+\frac{1}{n}} - (r-R_{plug})^{1+\frac{1}{n}}\right), \tag{2}$$

where R_{plug} is the plug radius and is related to the fluid yield stress according to:

$$R_{plug} = \frac{2L\tau_y}{\Delta P}. \tag{3}$$

It will be noted that the Herschel–Bulkley model can easily be modified to describe the power-law, Bingham plastic as well as Newtonian models [22]. The identification of the transition between laminar and turbulent flow is of great importance because the fluid flow behaviour changes fundamentally at the transition zone. Slatter and Lazarus [23] formulated a Reynolds number (Re_2) for non-Newtonian pipe flow:

$$Re_2 = \frac{8\rho V^2}{\tau_y + K\left(\frac{8V}{D}\right)^n}. \tag{4}$$