Measurement and Analysis of Flow Behaviour in Complex Geometries using Ultrasonic Velocity Profiling (UVP) Technique

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In order to derive models for estimating fluid momentum and kinetic energy in complex geometries, the shape of the velocity profile is critical in determining accurate quantities. In some applications, such as flow through pipe fittings and flow through abrupt contractions and enlargements, theoretical velocity profiles in combination with mathematical models have thus far been used to determine fluid momentum, kinetic energy and loss coefficients. In this project a non-Newtonian CMC model fluid was tested in two different complex geometries using the Ultrasonic Velocity Profiling (UVP) technique. Velocity profiles were measured at three different positions at the center (contraction) of a specially manufactured 50% open diaphragm valve. A range of velocity profiles from developed to contracting flow were also measured by scanning the transducer along a hyperbolic contraction using a high precision robotic arm set-up. Experimental results obtained using UVP showed good agreement with theoretical predictions. Results showed that the most important problem is that it is not possible to accurately measure from the transducer front, which is due to the ultrasonic transducer's near-field. Wall interfaces could be calculated to a certain degree of accuracy, but information of the high velocity gradient close to the wall region is still inaccurate, which could influence results significantly. This problem can be eliminated by the introduction of a next generation transducer, which is currently under development.

Keywords: Velocity profiles, Complex geometries, Diaphragm valve, contraction-expansion, non-Newtonian

1 INTRODUCTION

Flow through complex geometries such as abrupt contractions and enlargements, as well as valves are important problems in fluid dynamics, because they are integral components and frequently occur in pipeline systems. In order to design pipeline systems efficiently, understanding the energy loss mechanisms in complex geometries is a prerequisite [1]. According to literature, there are many different techniques for studying flows of multiphase and complex fluids. However, experimental and cost limitations forces one to consider an alternative approach [2]. UVP is both a method and a device to measure an instantaneous unidimensional (1D) velocity profile along a measurement axis [3-5] and is accepted as an important tool for measuring flow profiles in opaque liquids used in research and engineering. This method has been used for flow mapping in complex geometries such as stirred tanks [6], open channel [7], contractions [8-9], liquid metal target of neutron spallation source configuration [10] and cylindrical hydrocyclone [11].
In this work velocity profiles were measured using UVP at the center (contraction) of a specially manufactured diaphragm valve and at multiple positions along a hyperbolic contraction. The industrial applicability of the UVP technique for measurement of non-Newtonian flow behaviour in two complex geometries was evaluated in this work.

2 THEORY

2.1 Pipe flow

The radial velocity profile for non-Newtonian shear-thinning pipe flow can be described by the integrated form of the power-law model:

$$v = \left(\frac{nR}{(1+n)}\right)\left(\frac{R\Delta P}{2LK}\right)^{\frac{1}{n}}\left(1-\left(\frac{r}{R}\right)^{1+\frac{1}{n}}\right). \qquad (1)$$

In pipe flow integration of the velocity profile yields the volumetric rate of fluid flow and is given by:

$$Q = 2\pi \int_0^R vr dr, \qquad (2)$$

where v is the velocity at a radial point, r, along the pipe radius. The volumetric flow rate, Q, in a steady state process is given by:

$$Q = VA, \qquad (3)$$

where V is the bulk velocity and A the total area of a particular geometry [12]. In order to calculate a flow rate from measured velocity profiles inside the valve center geometry, separate flow rates were calculated for manually drawn area/flow segments (see Fig. 2) and added together to yield a total volume flow rate:

$$Q_T = \sum_{n=1}^{N} \left(V_n \cdot A_n\right), \qquad (4)$$

where V_n is the measured velocity across a particular flow/area segment, A_n, which is calculated by Solidworks 2009 and N is the total number of segments.

3 MATERIAL AND METHODS

3.1 Material

The Carboxymethylcellulose (CMC) (Protea Chemicals, Bryanston, South Africa, http://www.proteachemicals.co.za) solution used was 6.15% w/w for the valve tests at FPRC. CMC sodium salt (Alfa Aesar GmbH & Co KG, Karlsruhe, Germany, www.alfa.com) 2.63% w/w was used for the hyperbolic contraction tests at SIK. Controlled stress rheometers (Paar Physica MCR300, Anton Paar, Randburg, South Africa, www.advancedlab.co.za and Rheologica StressTech, Rheologica Instruments, Lund, Sweden) were used to obtain flow curves for the CMC 6.15% w/w (K = 0.07, n = 0.85) and 2.63% w/w (K = 0.68, n = 0.82) solutions (cup and roughened bob geometry, measuring gap = 1.13 mm). The rheological parameters were used to calculate Reynolds numbers [13] for non-Newtonian pipe flow. In this research all measurements were conducted in laminar flow.

3.2 Experimental flow loops and UVP setup

In this work the latest UVP instrument (UVP-DUO-MX, Met-Flow SA, Lausanne, Switzerland) was used for velocity profile measurements. Ultrasonic Doppler, Immersion type transducers (TN and TX-line, Imasonic, Bensancon, France) with a base frequency of 4 MHz, 5 mm active element were used [14]. A special flow adapter cell made from stainless steel was designed at SIK for simultaneous in-line measurements of velocity profiles and acoustic properties for straight pipe flow. This transducer installation has previously been described [4, 15] and the same setup was used for the valve tests in this work. Two experimental flow loops were used in this work, one for the valve and one for the contraction flow measurements. Both flow loops share similar methodology of equipment setup and transducer installation. The first flow loop (valve) consisted of a 52.8 mm PVC pipe and is fully described elsewhere [16]. The second flow loop (contraction) consisted of stainless steel pipes of internal diameters 48.5 and 22.5 mm and is described in Zatti *et al*. [9]. Fig. 1 shows a schematic diagram of the valve flow loop at the FPRC.

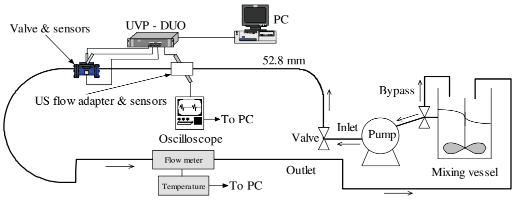

Fig. 1. Schematic illustration of the valve flow loop.

3.3 Diaphragm valve

A commercial diaphragm valve (Dynamic Fluid Control Pty Ltd, Johannesburg, South Africa, www.dfc.co.za) was reverse engineered and re-manufactured using a rapid prototyping (3DP™) technique of multilayer printing [17]. The spatial co-ordinates of the valve were obtained from 3D imaging using a special camera and were relayed to a CAD drawing package, Solidworks 2009 (Dassault Systèmes SolidWorks Corp., Concord, MA, USA, www.solidworks.com). With the valve geometry known, it was then possible to design and create ports in which to install ultrasonic transducers in the valve, especially with regard to, and as close as possible to the valve center. Information from the CAD drawing was relayed to a 3D printer (Z-Corp., Burlington, MA, USA, www.zcorp.com), which was used to grow the 3-dimensional object. Fig. 2 shows both the design and the positions (TDX Lines 1-3) of the ultrasonic transducers at the center valve geometry.

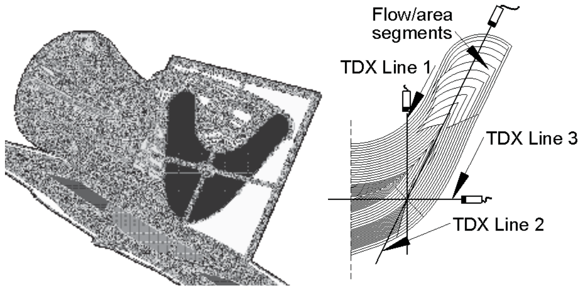

Fig. 2. Isometric view of diaphragm valve design and transducer positions.

3.4 Hyperbolic contraction

Fig. 3 shows the experimental setup for the contraction tests. The hyperbolic contraction used in this work was made of Polymethylmethacrylate (PMMA). The contraction was installed in a 20 l tank and was filled with CMC, thus using it as a coupling fluid. The contraction wall thickness was also optimised to integers of half wavelengths for maximum ultrasonic energy transfer. In this case velocity profiles were measured through the contraction wall interface and not by installing transducers in direct contact with the test fluid, as described for the valve tests.

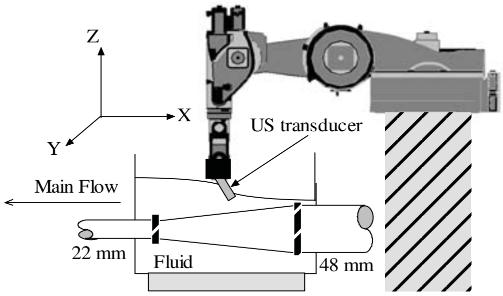

Fig. 3. Contraction setup with robotic arm.

The ultrasonic transducer was moved along the contraction (X-direction) using a high precision (+/-0.03mm) robotic arm (KUKA Roboter GmbH, http://www.kuka-robotics.com). This enabled measurement of a range of velocity profiles from developed to contracting flow and from the results a complete flow map of the velocity field inside the hyperbolic contraction was determined. More details are presented elsewhere [9].

4 RESULTS AND DISCUSSION

4.1 Valve geometry

Velocity profiles measured at three different flow rates (0.5 l/s, 0.99 l/s, 1.7 l/s) inside the valve across TDX Lines 1-3 (see Fig. 2) is shown in Figs. 4-6. Results obtained from measurements across TDX Line 3 are symmetrical around the center position (dotted lines) and was expected due to measuring across a symmetrical axis in the valve. Fig. 5 shows a sharp increase in velocity close to the near wall for all of the lateral measurements.

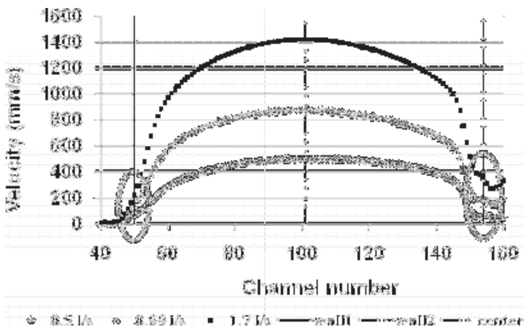

Fig. 4. Radial profiles measured in valve across TDX Line 3 for CMC 6.15% w/w.

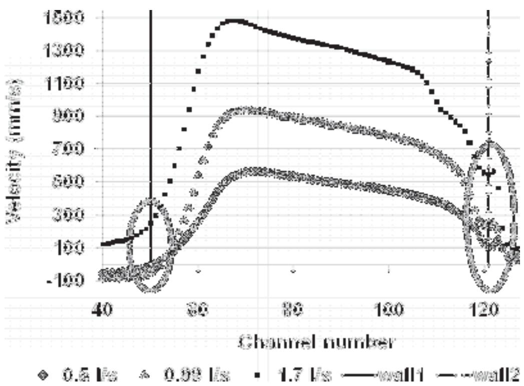

Fig. 5. Lateral profiles measured in valve across TDX Line 1 for CMC 6.15% w/w.

This could be due to the fluid pushing against and under the diaphragm creating higher velocities than compared with velocities measured at a different position in the valve. Velocity profiles measured across the diagonal position (TDX Line 2) shows an increase of velocity from the near wall and steady decrease from the center area of the valve. What is interesting is that at higher flow rates the linear increase of velocity from the near wall to the maximum velocity (as in the 0.5 l/s case) seems to stay constant for some distance, which suggest that most of the fluid flow occurs beyond the valve's upper regions or 'ears'.

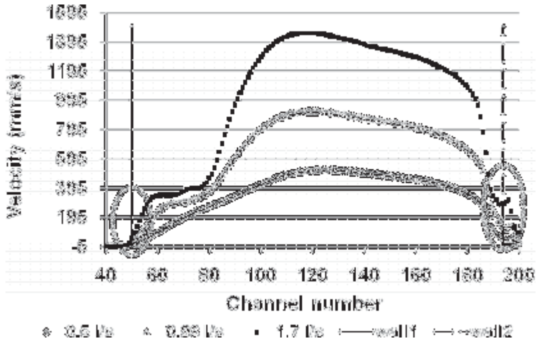

Fig. 6. Diagonal profiles measured in valve across TDX Line 2 for CMC 6.15% w/w.

It can be observed that every experimental velocity profile has non-zero velocities (marked with circles) at the wall interfaces (marked with solid and broken lines, wall1-wall2). Firstly, the increase in velocity at the first wall interface (wall1) is due to the cavities situated in front of the transducer surfaces, where flow occurs before the actual wall position. The increase in velocity at the opposite wall interface (wall2), is due to multiple ultrasonic reflections from the wall, which is inherent in UVP [4]. A velocity distribution colourmap, constructed using Solidworks and Matlab, is presented in Fig. 7.

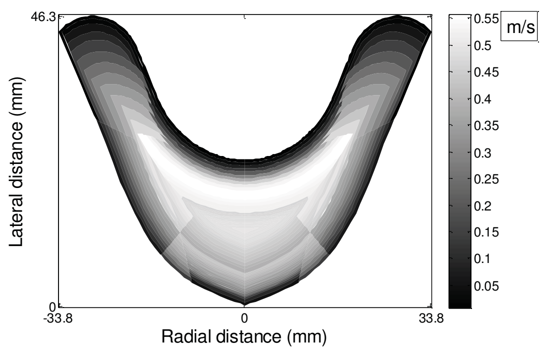

Fig. 7. Velocity distribution 3 colourmap.

The measured volume flow rate was 0.5 l/s and the error difference percentage between the calculated flow rate (0.43 l/s) was 14.86%. Some important observations can be made from the colourmap in Fig. 7. The majority of the flow seems to be at the center area of the valve and not at the upper regions (see Fig. 6). Also, the highest measured magnitudes of velocity appear to be just below the valve diaphragm (see Fig. 5).

4.2 Hyperbolic contraction

Fig. 8 shows the theoretical and experimental velocity distribution inside the hyperbolic contraction using Eq. 1 and UVP. The average error difference percentage between the theoretical and experimental results was 10.37%.

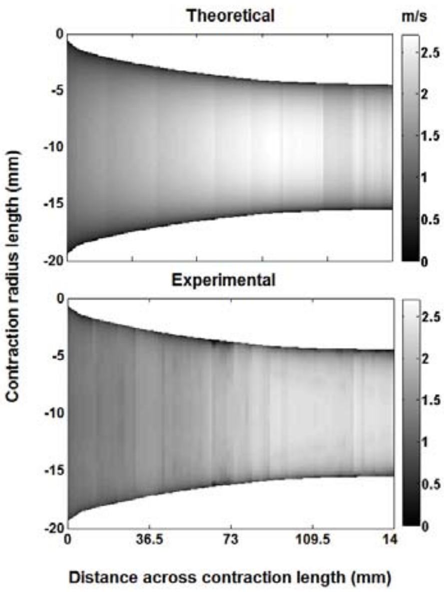

Fig. 8. Experimental and theoretical velocity distribution across contraction length for CMC 2.63% w/w.

This error was mainly due to the temperature dependant properties of the CMC sodium salt, which showed a decrease in viscosity with increasing temperature from fluid pumping effects. A significant amount of energy is required to overcome ultrasonic absorption and penetration depths when measuring through material layers. This loss of energy can also cause problems when measurements inside attenuating fluids are of interest, which is the case with most industrial suspensions.

5 SUMMARY

From our results we conclude that UVP is a suitable method for measuring velocity distributions inside complex geometries. The most important remaining problem in order to increase overall measurement accuracy is velocity measurements from the transducer front at the wall region, where velocity gradients are high. This problem could be reduced by the introduction of new ultrasonic transducers that allows measurements directly at the transducer front. A transducer of this kind where the focal point of the ultrasonic beam is located at the transducer front/wall, is currently under development [4].

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