

Determination of Velocities Profiles in Hyperbolic Contraction using Ultrasound Velocity Profiling

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ABSTRACT

A shear-thinning model fluid was studied in hyperbolic contraction flow. The sample was pumped through the hyperbolic nozzle, designed to give a constant extension rate. The velocities profiles throughout the nozzle were determined using Ultrasound Velocity Profiling.

The radial velocity profiles measured were found similar to the theoretical. Axial velocity profiles confirmed the design criteria of constant extension rate throughout the nozzle.

INTRODUCTION

Measurement of rheological properties is, for the modern food industry, a simple and essential way to evaluate technological parameters and monitoring possible variations of important product's properties. Many food systems cannot be described as Newtonian fluids, they are elastic and during processing or final consuming are often subjected to certain types of flow which include extensional components, thus cannot be described solely using shear viscosity, η ¹.

These types of flow involving extensional components are often described by the extensional viscosity, η_E , which is always higher than η and can behave in a total different way.

Despite the well-known importance of η_E in manufacturing and final consumer mouth feel, the available measurement techniques are still difficult and time consuming and they cannot be implemented in-line.

In this context a novel technique was studied with the aim of measuring the extensional viscosity in-line, quickly and without compromising the hygienic requirements imposed by the food legislations².

The food sample was subjected to extensional flow in hyperbolic contraction flow geometry³⁻⁵ and then utilizing Ultrasound Velocity Profiling-Pressure Difference (UVP-PD) technique⁶, several radial velocity profiles were measured directly inside the contraction flow geometry.

THEORY

Measurements of rheological parameters in-line were performed in hyperbolic contraction flow³, using the experimental set-up shown in Fig. 1.

The fluid was pumped through the hyperbolic nozzle by a positive displacement pump at constant flow rate Q . Measurement of the stresses were indirectly done measuring and recording the pressure drop between the inlet and outlet sections of the hyperbolic nozzle through a membrane pressure transducer.

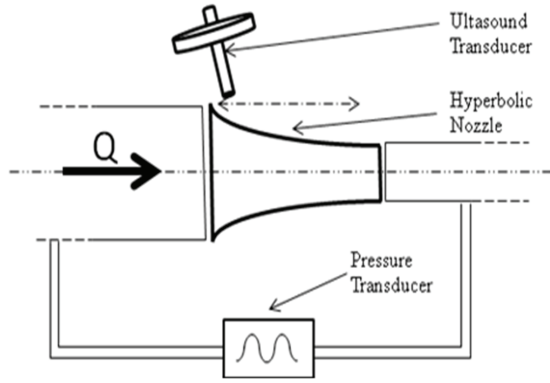


Figure 1. Scheme of the UVP-PD measurement plant with hyperbolic nozzle.

The contraction nozzle is designed to give an extensional strain rate, $\dot{\epsilon}$ constant throughout the length of the nozzle at a constant flow rate. Fig. 2 is an illustration of the contraction nozzle, which can be designed as:

$$r(z) = \frac{r_0}{\sqrt{\frac{z}{H} \left(\frac{r_0^2}{r_1^2} - 1 \right) + 1}} \quad (1)$$

The radius at the nozzle inlet is r_0 , the radius at the nozzle outlet is r_1 , the radius at z is $r(z)$, Q is the volumetric flow rate calculated integrating one of the velocity profile measured with the UVP, while H is the length of the nozzle.

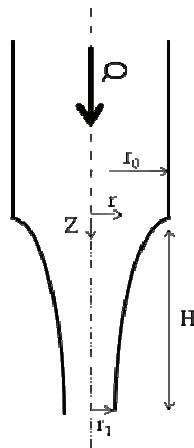


Figure 2. The contraction nozzle.

The constant strain rate in the nozzle is:

$$\dot{\epsilon} = \frac{3n + 1}{n + 1} \frac{Q}{\pi} \frac{r_1^{-2} - r_0^{-2}}{H} \quad (2)$$

Ultrasound Velocity Profiling

Ultrasound velocity profiling (UVP) represent both a method and a device for measuring an instantaneous velocity profile in a liquid flow along the ultrasonic beam axis. The principles of the UVP operation are illustrated in Fig. 3.

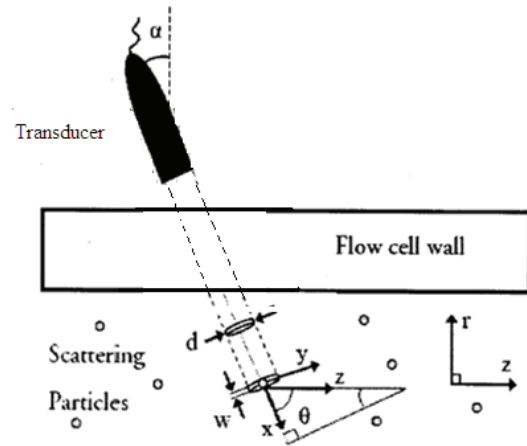


Figure 3. Principle of the Pulse Doppler Method.

The ultrasound transducer with an active diameter d , and inclined with an angle α , transmits a short sinusoidal ultrasonic pulse into the flowing liquid. When the ultrasonic pulse hit a small moving particle suspended in the model fluid, part of the ultrasonic energy scatters on the surface and echoes back.

Meanwhile the transducer is switched to receiving mode directly, and the time interval between two successive pulses is available for echo reception. If the scattering particles are moving, the received echo is shifted and trough a time domain signal processing the axial velocity of the particles is calculated.

Validation and control

Validation of the measurement was done comparing the shape of theoretical velocities profiles in different positions along the

nozzle with the real velocities profiles measured with the UVP technique.

The theoretical velocities profiles were calculated finding the relative pressures (ΔP) at different positions for a power law fluid, as⁷:

$$\Delta P = \frac{2LK}{R^{3n+1}} \left(\frac{Q}{\pi} \right)^n \frac{1}{\left(\frac{n}{3n+1} \right)^n} \quad (3)$$

The radial velocities profiles were given by:

$$v(r) = \left(\frac{\Delta P}{2LK} \right)^{\frac{1}{n}} \frac{R^{1+\frac{1}{n}}}{1 + \frac{1}{n}} \left[1 - \left(\frac{r}{R} \right)^{1+\frac{1}{n}} \right] \quad (4)$$

where L is the distance between the pressure sensors, r corresponds to a radial coordinate measured from the nozzle's centre and R is the outer pipe radius.

MATERIALS AND METHODS

Materials

Pectin (Grinsted[®] Pectin CF 120) and CMC (Grinsted[®] Cellulose gum NMD 150) were kindly provided by Danisco (Danisco A/S – Textural Ingredients, Copenhagen, Denmark).

The ultrasound transducer was a 4MHz with an active diameter of 5 mm (TN, Imasonic, France) coupled with the latest available velocity profiling instrument with a multiplexer unit (UVP-Duo-MX, Met-Flow, SA, Lausanne, Switzerland). A four channel oscilloscope (54624A, Agilent Technologies, Santa Clara, CA, USA) was used as an integral part of the data acquisition scheme, enabling simultaneous measurements of the flow velocity profiles and monitoring other important parameters. The UVP-Duo instruments and the other hardware devices were connected to a master PC via Ethernet and a DAQ card (National Instruments Sweden AB, Solna, Sweden). Communication with UVP-Duo hardware was implemented with an Active X Library driver, supplied by Met-Flow SA.

The UVP-Duo and the Met-Flow Software enable velocity profiles' acquisition with a time domain algorithm directly on the DSP.

Preparation of the model fluid

In the present study the model fluid have a basic formulation composed of pectin (4.5% w/w), CMC (0.5% w/w) and deionized water.

To prepare the continues phase the CMC and the pectin were dispersed (40°C) and stirred for 60 minutes to facilitate hydration. The sample was later kept overnight at room temperature to fully hydrate and later homogenised at 16000 rpm for 15 min.

Methods

The contraction flow instrument and UVP techniques is a prototype from SIK (Goteborg, Sweden) as described above.

RESULTS AND DISCUSSION

Validation and control

Comparing these real velocities with the theoretical calculated from Equation 3 and 4 and shown in Fig. 5, it is possible to observe the similar shape of the measured (Fig. 4) and predicted (Fig. 5) velocity profiles, proving the quality of this test and consequently the quality of the technique applied.

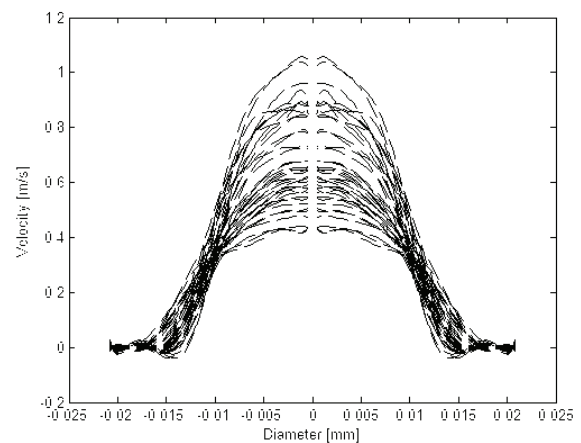


Figure 4. Measured velocities using UVP-PD technique.

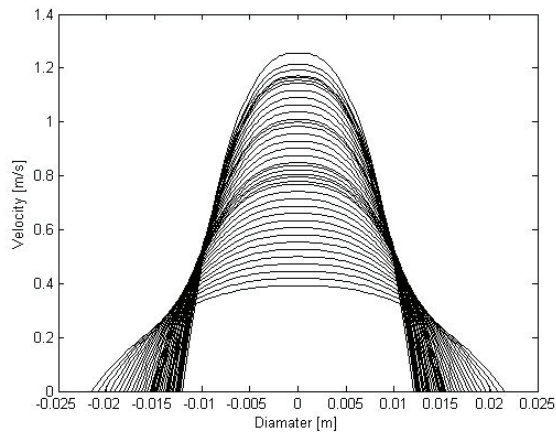


Figure 5. Theoretical Velocity Profiles.

An important results derive from the data collected with the UVP, is the velocity along the length of the nozzle, for all the section from the wall till the centre of the pipe. These axial velocities are predicted to be linear³, corresponding to a constant extension rate. The observed axial velocity profiles are close to linear. The discrepancy from linear profiles arise from measuring difficulties close to the entrance (axial distance > 0.08 m in Fig. 6).

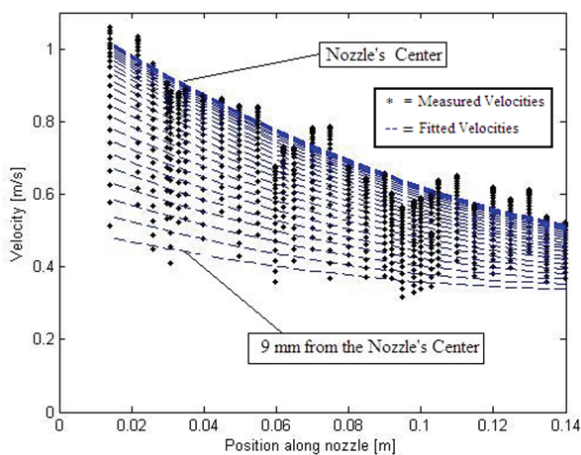


Figure 6. Measured velocities along the nozzle, from the exit to the entrance. The lines are guidance for the eye.

CONCLUSION

- The velocities measured using the UVP-PD technique were reliable resembling predicted velocity profiles.

- Axial velocities parallel to the nozzle's main axis were almost linear confirming the theory used for designing the nozzle.

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