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STUDY OF FLOW PROCESSES OF CONCENTRATED SUSPENSIONS USING IN-LINE NON INVASIVE RHEOLOGICAL TECHNIQUE

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Introduction

To detect changes in the quality of food materials, related to the microstructure of the food system already in the production process, the rheological flow behaviour of the in general non-Newtonian, highly concentrated and non–transparent fluid is a powerful "tool" if it can be measured in-line. Commercial process rheometers are usually not suitable for this purpose because of their size, cost and destructive methods they are based on.

In our approach we mainly consider pressure driven laminar shear flows of highly concentrated non-transparent food suspensions which are transported in the most of the production processes of interest in cylindrical tubes. An emphasis made on development of measurement cell accommodating an Ultrasound Velocity Profiler (UVP X3, Met-Flow SA) Doppler system and two micro pressure transducers for in-line viscosity sensing.

As one of application solutions the authors introduce direct inline measurements conducted in transporting pipe of chocolate crystallisation process. In particular case the process influences the crystal fraction in the chocolate suspension, and thus strongly affects the flow properties (rheology) as well as a variety of quality characteristics like stability, texture, spreadability and taste of the final product.

The crystallisation process is sensitive to slight modifications of the structure of the chocolate suspension mainstream. Injection of defined type and amount of crystals into the liquid phase of the chocolate suspension influence the final quality of the product. Since the product is non-transparent and very sensitive to slight temperature, flow velocity and applied deformation changes, no other alternative could be found for precise on-line structure state monitoring.

Experiments

The developed in-line measured cell was adapted and installed in an industrial chocolate crystallisation process. The cell consists of a straight pipe section with 32-mm diameter (DIN 32). A 4 MHz UVP X3 was used for in-line flow visualisation in the sectional tube channel which is a part of the process transporting pipe (see Figure 1).

Simultaneously, the wall shear stress was measured using so-called pressure difference method with two flush-mounted pressure transducers. Besides, temperature sensors incorporated in the pressure transducers are used for temperature measurement in the flow channel.

A new data acquisition system with software was created for precise rheological on-line calculations and monitoring (see Figure 2).

The shape of the measured velocity profiles was approximated using the power law model and was correlated with the crystals concentration in the chocolate suspension. The shear rate distribution was computed from the UVP velocity profile values. The fit velocity profile was used for volumetric flow rate calculation. A pressure difference was calculated from the mean values of smoothed raw pressure signals. Further calculations of the wall shear stress and shear stress distribution along the diameter distance was performed. During the last step the shear viscosity function is composed from shear rate and shear stress distributions.

The process consists of two production procedures. During the first one, a fixed amount of 0.14 % *Cm* (mass concentration) crystals is injected into the liquid phase of the chocolate suspension. During the second one, an amount of 0.05 % *Cm* was injected. The influence of only 0.1 % *Cm* additional crystals could be recorded as a change in power law exponent *n* (see Figure 5) and shear viscosity function (see Figure 6).

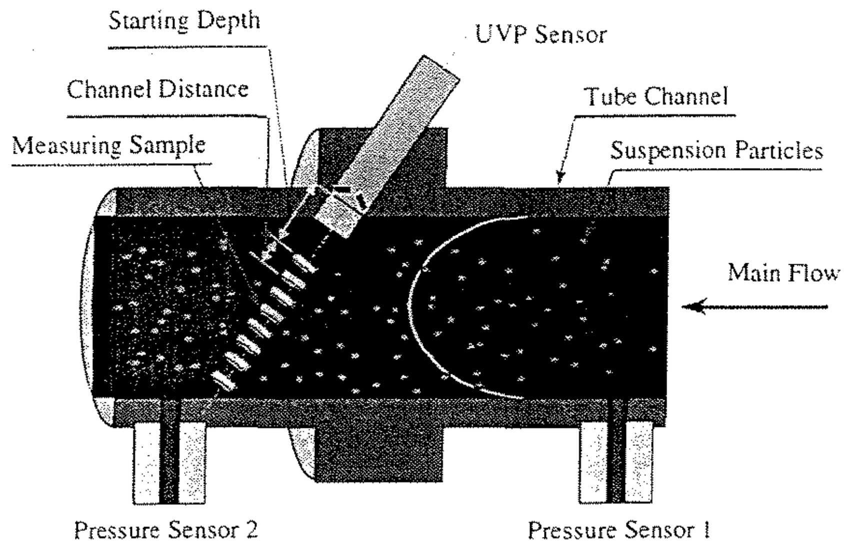

Figure 1: Schematic of the shear stress adapter with pressure sensors installed in the sectional transporting pipe with the distance L = 990 [mm] apart. It also shows a basic parameters used in flow visualisation set-up of the UVP sensor

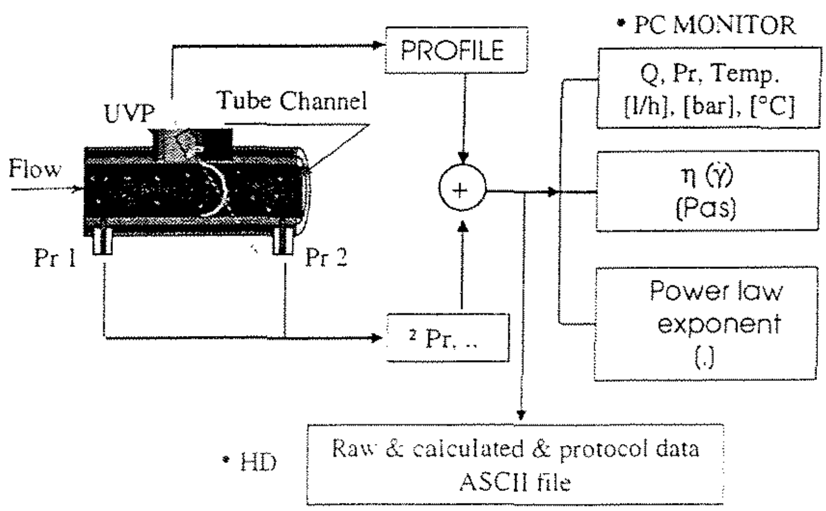

Figure 2: General data flowchart of In-line Rheometer: measurement, real time monitoring and storage of raw and calculated data.

A general data flowchart is shown in Figure 2. The on-line monitor (see Figure 2) is active throughout the measuring sequence. The information on the monitor is renewed consequently with the new incoming data file from the UVP monitor.

Results and Discussion

The measured time averaged flow velocity *Vx(r)* profiles along the diameter distance *Dd* are shown in Figure 3. The result of the on-line power law fit procedure is introduced (see Figure 4) in a form of calculated velocity profile. Using a Herschel-Bulkley approximation a yield stress could be derived from the averaged raw velocity profile and compared with the measurement of conventional rotational rheometer.

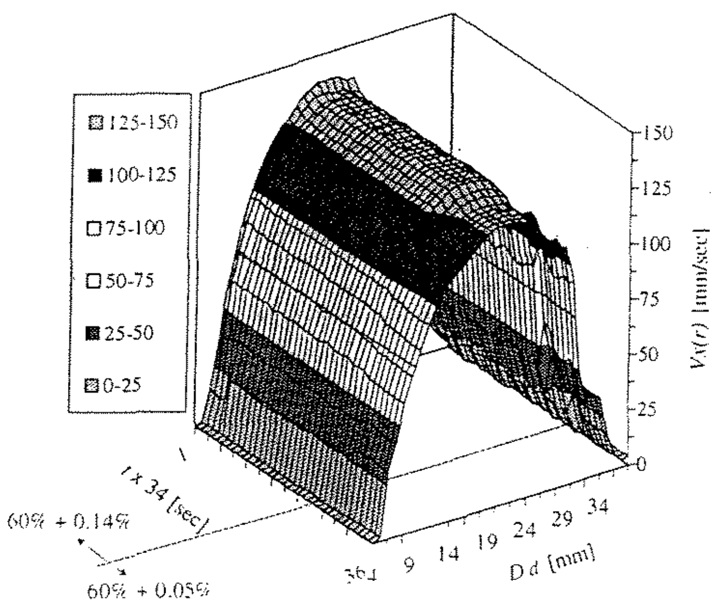

Figure 3: A 3D time series chart of raw velocity profiles of concentrated chocolate suspension (solids concentration greater than 60 % Cm); the average time between two velocity profile recordings varies between 30 and 34 sec.

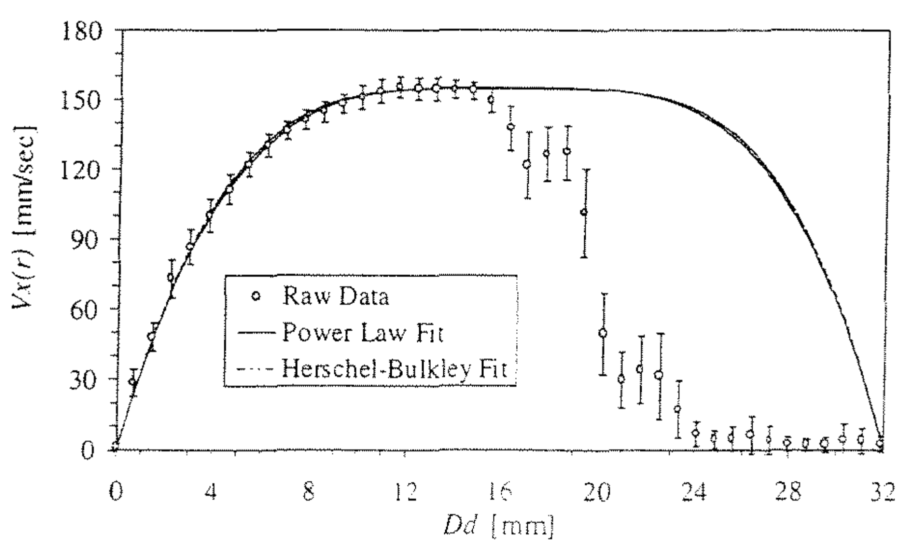

Figure 4: A 1D raw velocity 'Vx(r)' profile of chocolate suspension: power law and Herschel-Bulkley fit are shown as a solid and dashed lines and measured values as symbols.

According to shown in Figure 4 Herschel-Bulkley fit gives an output parameters as radius of the plug $R^* = 1.5$ [mm] and power law exponent $n = 0.4$. The wall shear stress and the yield stress value could be approximated from the pressure head loss $\Delta P = 0.057$ [bar] measured along the length distance $L = 990$ [mm]. The yield stress measured in-line exceeds value of $\tau_0 = 4.32$ [Pa] in comparison with the off-line rotational rheometer measurement of yield stress approaching $\tau_0 = 4.52$ [Pa].

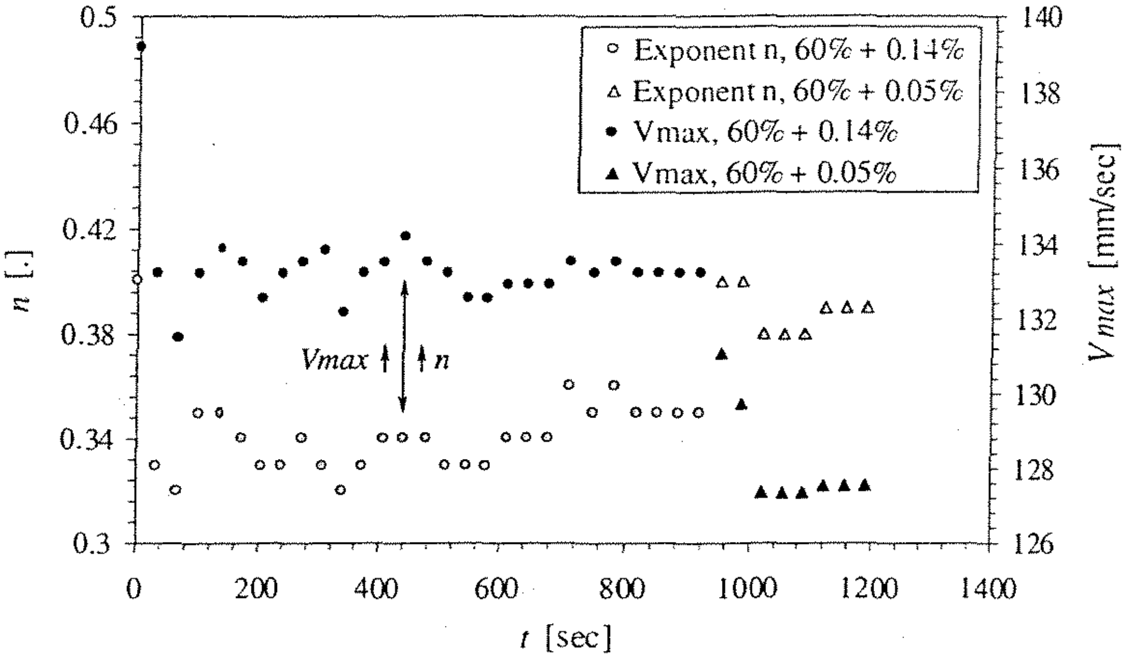

Figure 5: Comparison between maximum flow velocity 'Vmax' and power-law exponent 'n' as a function of time 't'.

With increasing of the flow velocity $Vx(r)$ the structure of chocolate suspension is exposed to faster deformation rate, which is followed by slightly delayed dispersing of the structural network. The opposite reaction of the structure is found during decrease of the flow velocity. This can be observed on-line from the "in phase" fluctuations of the power law exponent n with the maximum flow velocity fluctuations.

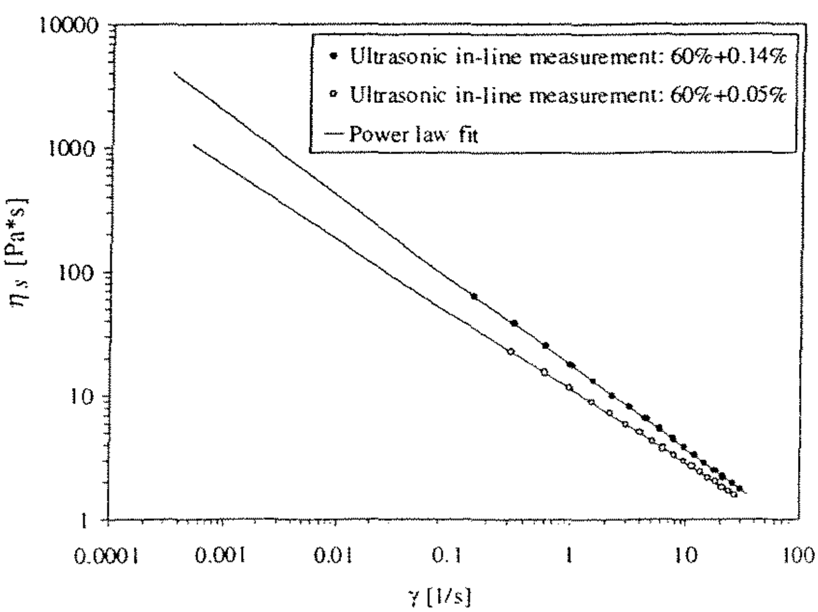

Figure 6: Shear viscosity function 'η_s' computed and monitored on-line every 30 sec.

An increase in effective concentration of solids on 0.1 % Cm distinguishably changes the slope and offset of the shear viscosity function (see Figure 6).

The measured rheological quantities, namely the shear viscosity function (see Figure 6) and power law exponent *n* (see Figure 5), described the structural state of the chocolate suspension in the industrial crystallisation process and enable a continuous process monitoring.

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Literature

Takeda, Y
Measurement of flow phenomena using the ultrasonic velocity profile method in a simulated Cyochralski crystal puller. Journal of crystal growth, 1993 June.

E. Windhab, B. Ouriev, T.Wagner, M. Drost
Rheological study of non-Newtonian fluids
(Abstract) Proceedings of the 1st International Symposium on Ultrasonic Doppler Methods for Fluid Mechanics and Fluid Engineering, Villigen PSI, Switzerland (1996)

B. Ouriev, Prof. E. Windhab.,"Slit rheometry for testing of a new on-line measuring system", proceedings of the Food Rheology Congress, March 1997, Zurich.

Ouriev. B, Windhab E.
Slit rheometry for testing of a new on-line measuring system
Proceedings of the Food Rheology Congress, pp. 378-383, (March 1997), Zurich

Ouriev B., Windhab E.
In-line rheological measurements and flow visualisation using Doppler ultrasound method.
5th European Rheology Conference, Extended Abstract, Proceedings (, September 6-11, 1998), Ljublijana, Slovenia.

Ouriev B., Windhab E.
On-line rheological measurements and process monitoring using flow visualisation of non-transparent highly concentrated multiphase systems using Doppler ultrasound method.
International Conference on Colloid Chemistry and Physical-Chemical Mechanics, Abstract, Proceedings, pp. 232 (October 4-8, 1998), Moscow, Russia.