Potential of Ultrasound-Doppler in process flow measurements along the food value chain

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The so called “Food Value Chain” starts at the environmental level and related conditions for the agricultural production of food/food raw material and ends with the metabolic/biological response of the human body to specific food intake and digestion. Most important in between domains are the (i) harvesting of food raw material, (ii) in factory processing of food products, (iii) home processing/meal preparation, (iv) eating of the food (mastica-tion, swallowing) and (vi) food digestion in the gastro intestinal tract. In all of these domains the flow of the food and/or its environment plays a crucial role from a processing perspective. In many of the related flows the food matter or involved processing systems are of multiphase nature containing one or more disperse phases of cer-tain size distributions and concentrations leading generally to high turbidity of the fluid. As a consequence optical access for velocity field measurements either by e.g. Laser Doppler Anemometry (LDA) or Particle Imaging Velocimetry (PIV) are not possible due to their restriction to low disperse phase fractions. At higher disperse phase concentration than about 2-5% vol. multiphase fluid systems in addition no longer behave as Newtonian fluids with constant viscosity, but show pronounced non-Newtonian shear thinning and/or shear thickening as well as thixotropic or rheopectic rheological behaviour. Ultrasound-Doppler (USD), ultrasound attenuation (USA) and the coupling of these with local pressure gradient detection (PD) based flow measurements in multiphase fluids up to high disperse phase fractions have been proven for their great potential in (A) flow mapping of complex velocity fields, (B) inline rheological analysis as well as (C) detailed inline micro structure characterization. Such advanced and versatile toolbox of inline measuring technics is of major importance for multiphase fluid system measure-ments the relevance of which is particularly addressed in this article along the Food Value Chain. - Examples are addressed for the domains of (1) environ-mental flows of rivers being of crucial importance for irrigation of agricultural areas, (2) in-factory processing of concentrated food suspensions and of (3) gastro intestinal flow patterns of interest for medical diagnoses and nutritional impact of flows in the human digestive tract.

Keywords: Ultrasound-Doppler, Flow mapping, In-line rheometry, Ultrasound spectroscopy, Particle Imaging Velocimetry (PIV), food value chain,

1 INTRODUCTION

The so called “Food Value Chain” (FVC) addresses human food from genesis of its raw material components to its digestion and metabolic/biological response in the human body. Accordingly (i) the environmental level and related conditions for the agricultural production of food/food raw material form initial boundary conditions followed by (ii) harvesting of food raw material, (iii) in factory processing of food products, (iv) home processing/meal preparation, (v) eating of the food (mastication, swallowing) and (vi) food digestion in the gastro intestinal tract. In these FVC-domains (i-vi) numerous multiphase flow cases with turbid fluid systems are of relevance for detailed investigations by (A) flow mapping, (B) inline rheological analysis or (C) inline micro structure (-development) characterization. For the FVC domain (i) environmental flows being e.g. of crucial importance concerning irrigation of agricultural areas have been exemplarily investigated in /1-3/ generally focussing on flow mapping. Harvesting technologies (FVC (ii)) may apply US-based volume flow rate measurements restricting to the detection of an average flow velocity using one- or two-way US time of flight (TOF) methods. The two-way approach is advantageous being independent of sound velocity in the fluid /4,5/. There is big potential in improving accuracy by USD-based whole velocity profile measurement and its integration. For FVC domain (iii) in-factory processing of turbid multiphase food systems represents the widest frame of USD and USA applications even though most of the solutions worked out so far still restrict to batch and lab-scale processes /6-11/. Robust in-line devices for industrial production applications are still requested particularly with respect to in-line rheometric and -structure analysis. Complex flow mapping applications are mostly restricted for use in process development. When it comes to the FVC domain (iv) of home processing there is still a “white spot” for US applications in general. However the vivid development activity to enter into more complex automated home processing device setups in the field of personalized food and nutrition is expected to also lead to an increased demand in accurate process (e.g. flow rate) and product (e.g. rheology and structure) control. This will most probably trigger the USD or USA application demand in the field. Concerning the FVC domains (v) and (vi), existing USD and USA applications in the gastro intestinal tract concern the field of related medical diagnosis devices using different or coupled US-modes /11-14/. A further detailed description of US (USD, USA, TOF) measuring techniques in the identified processing domains along the FVC will be given and discussed.

2 US-MEASUREMENTS AND TECHNIQUES

Recent developments of Ultrasound Doppler transducers performing in a wide range of frequencies from about 1 to 40 MHz as well as with higher sound power (>60-100W) and improved signal to noise ratio implementing also novel powerful signal processing setups, have made ultrasound flow measurement technologies a suitable toolbox-base for a wide range of applications in food and related industries along the food value chain.

2.1 Environment and agricultural production (i)

Hydrological measurements are essential for the interpretation of water quality data and water resource management. Variations in hydrological conditions have important effects on water quality. In rivers, such factors as the discharge (volume of water passing through a cross-section of the river in a unit of time), the velocity of flow, turbulence and depth influence water quality. In lakes, the residence time, depth and stratification are the main factors influencing water quality. Ultrasonic echography (Ultrasound Doppler Velocimetry, UVP) was well approved for flow measurement in physical scale models and in real river and reservoir/lake systems with turbidity currents. The undisturbed flow monitoring enabled to capture precise velocity profiles in short time [1]. With acoustic Doppler current profilers (here: SonTek aDcp, Figure 1) three-dimensional velocity profiles using the Doppler shift principle (see also UVP) were successfully measured, whilst a (river, lake) bottom tracking function and acoustic backscatter were used to measure bed load velocity and estimate suspended sediment concentration [2].

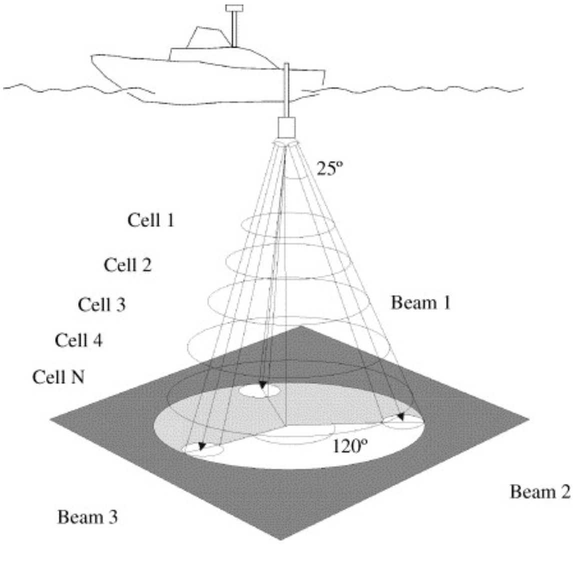


Figure 1: SonTek aDcp employing three (UVP) beams, with 1500 and 500 kHz transducers set at 25° from the vertical axis and equally spaced in the horizontal (120°), resulting in different orientations relative to the flow [2].

When it comes to the agricultural production of food raw materials, three major aspects of interest in ultrasound measurement applications can be summarized from literature: (1) Water management for irrigation and drainage systems [3,4], (2) Flows and water content in plant tissue [5-7] and (3) Investigations in farm animals [8,9].

2.2 *Harvesting of food raw material (ii)*

US-based measurements during harvest of food raw materials so far focuses on the quality monitoring of fresh fruit and vegetables in pre and post-harvest processes. The applied methods relate to sound velocity and US-attenuation measurements being correlated with plant tissue consistency and texture [10,11]. A typical measurement setup is demonstrated in figure 2. In this FVC domain so far the US-Doppler technique has only been introduced, for water flow rate measurements in washing and transport processes (see also ch. 2.1).

Among the indirect methods of food texture measurement, ultrasound technology provides one of the foundations for a non-destructive, fast and reliable technique for correlating specific quality-related indices and characteristics during growth and maturation, and in the course of storage and shelf-life, until readiness for consumption ([10]. Ultrasound techniques are relatively cheap, simple and energy saving, and thus have become an emerging technology for probing food products [11]. The mechanical structure of the tissue, its physico-chemical quality indices, and each change in the quality attributes of the plant tissue, affect the energy of the received signal. Ultrasound technology is suitable for quality measurement in various products such as porous food products ([10] as well as fruit and vegetables [11]. The most important mechanical property of fruit and vegetable that correlates with ultrasound characteristics is firmness and the results are most likely to be compared with destructive methods such as firmness tests ([10]. Figure 2 shows schematically a continuous wave technique. This technique, also called “through transmission”, utilizes two transducers located at both ends of a one way path. The sample cell is equipped with two quartz X-cut transducers that are placed apart by a known distance (L). A pulse generator is used to generate electrical continuous pulses with specific frequency and wavelength. A function generator is connected to the pulse generator to adjust the electric pulse before measurements. For accuracy, both of the ultrasonic signals and their equivalent temperature values are simultaneously recorded since the ultrasonic velocity through materials is temperature dependent. For controlled temperature measurements. As an alternative to the continuous wave technique a pulse-echo technique is as well widely used [12]. Table 1 gives an overview on US-analytics of selected food systems.

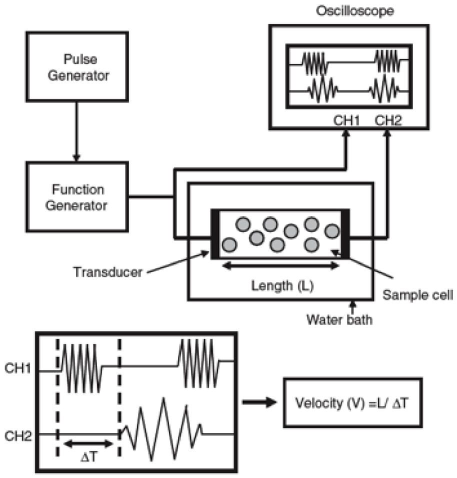


Figure 2: Scheme of an ultrasonic velocity continuous wave technique, and method of ultrasonic velocity (V) calculation. !T, time delay; CH1, standard signal; and CH2, measured signal [12].

2.3 In factory processing of food products (iii)

Ultrasound techniques are relatively cheap, simple and energy saving, and thus became an emerging technology for probing and modifying food products. Low power (high frequency) ultrasound is used for monitoring the composition and physicochemical properties of food components and products during processing and storage, which is crucial for controlling the food properties and improving its quality. High power (low frequency) ultrasound, on the other hand, induces mechanical, physical and chemical/ biochemical changes through cavitation, which supports many food processing operations such as extraction, freezing, drying, emulsification and inactivation of pathogenic bacteria on food contact surfaces. In factory processing has become the major development field for in-line US-Doppler applications concerning (A) flow mapping, (B) non-Newtonian rheometry and (C) microstructure characterization, within the past decade.

For (A)-(C) the use of US-transducers in the frequency range of 1-40 MHz offers a wide range of spatial resolution from about 10 micron to 10 cm. Spatial resolution in an ultra- sonic imaging system depends on a complex interplay of conditions being dictated by the beam and focal properties of the source (focal number, source bandwidth, etc.), tissue attenuation, nonlinearity of the medium, fluid inhomogeneity (phase abberation, spatial variations in the refractive index), and sound speed [13]. In ultrasound, axial resolution is improved as the bandwidth of the transducer is increased, which typically occurs for higher center frequencies. However, the attenuation of sound typically increases as frequency increases, which results in a decrease in penetration depth. Therefore, there is an inherent tradeoff between spatial resolution and penetration in ultrasonic imaging. One way to increase the penetration depth without reducing axial resolution is by increasing the excitation pulse amplitude. However, increased excitation amplitude results in increased pressure levels that could result in unwanted effects, e.g., heating or damage of fluid/ tissue structure. Therefore, increasing the excitation pulse amplitude is not always a viable solution. An alternate solution would be to increase the excitation pulse duration by using coded excitation, which increases the total transmitted energy and allows for the minimization of the transmitted peak power. However, elongating the signal duration has the negative effect of decreasing the axial resolution of the ultrasonic imaging system. In order to restore the axial resolution after excitation with a coded signal, pulse compression is used. Pulse compression can be realized by using many filtering methods such as matched filtering, inverse filtering, and mismatched filtering. A main disadvantage of using coded excitation and pulse compression would be the introduction of range sidelobes that can appear as false echoes in an image. The introduction of range sidelobes is a detriment to ultrasonic image quality because it can reduce the contrast resolution The main advantage cited for using coded excitation is that it is known to improve the echo signal-to-noise ratio (eSNR) by increasing the time-bandwidth product (TBP) of the coded signal. This improvement in eSNR results in greater depth of penetration for ultrasonic imaging and improved image quality; i.e., increased eSNR can actually in-crease contrast resolution. Furthermore, this in-crease in penetration depth allows the possibility of shifting to higher frequencies with larger bandwidths in order to increase the spatial resolution at depths where normally it would be difficult to image [13].

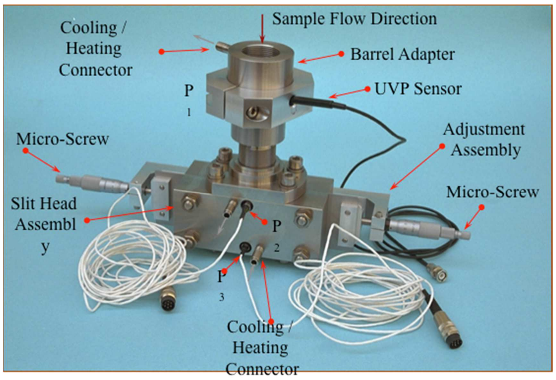


Figure 3a: Extruder die for in-line USD-flow mapping and pressure measurements [14]

2.3.1 Flow mapping – is still to be seen most relevant for basic flow investigations during a development period of flow / flow processing equipment and its adaptation or tailoring to fluid systems with complex rheology.

This may advance to in-line in-stallations in flow processes for permanent or perio-dic flow monitoring. Figures 3a and 3b demonstrate such a flow mapping setup for in-line measurements in an extruder die entrance domain [14].

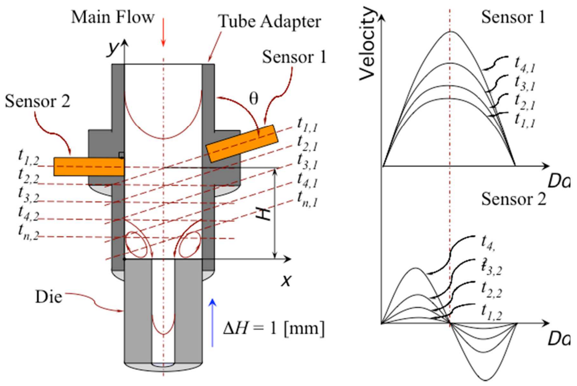


Figure 3b: Velocity vectors measured by USD-flow mapping in extruder die entrance flow domain [14]

There is major interest in the flow process engineering community to better access instationary process flow situations. A prominent example is the Taylor-Couette (TC) flow between concentric cylinders in an intermediate Re-number range between laminar and isotropic turbulent flow. A visualized TC vortex flow pattern and a related spatio-temporal velocity map taken by USD flow mapping are shown in figures 4 a and 4b [15,16].

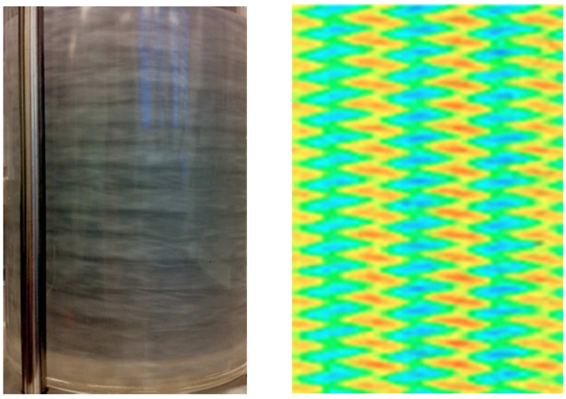


Figure 4a(left): Visualization of a Taylor-Couette vortex flow in transparent concentric cylinder gap; 4b(right): USD-measurement based spatio-temporal velocity map of Taylor-Couette vortex flow [17]

2.3.2 In-line Rheometry – has become an important issue with respect to processing and process control in complex fluid systems with non-Newtonian rheology. The shear/elongation stress and time dependencies of the rheology of many liquid or semi-liquid food systems and the close functional relationship between microstructure and rheology have brought in-line rheometry of such material systems into the focus for optimization of food processing and products as well as for related processing equipment.

The basis for USD-based in-line rheometry is the coupling of velocity profile (i) and radial pressure gradient (ii) measurements (UVPPD) in a laminar cylindrical pipe flow. From the radial derivative of (i) one gets the radial shear rate distribution (eq.1) [14]

$$\dot{\gamma}(r) = dv(r)/dr \qquad (1)$$

$$\tau(r) = dp/dx(r/2) \qquad (2)$$

(ii) delivers the radial shear stress distribution (eq.2). The viscosity function is then derived from Newton's shear stress law:

$$\eta(\dot{\gamma}) = \tau(\dot{\gamma})/\dot{\gamma} \qquad (3)$$

Figure 5a demonstrates a velocity profile measured by USD with a UVP (=Ultrasound Velocity Profiler) from Ubertone SA, Strassburg, F and the derived radial shear rate distribution. Figure 5b contains the related radial shear stress distribution for a highly concentrated suspension (untempered milk chocolate at 33°C) [18].

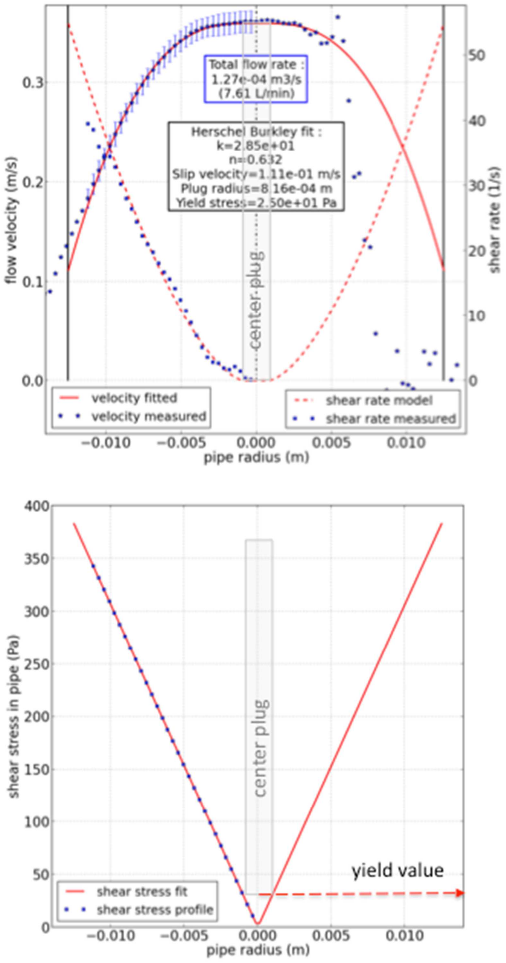


Figure 5a: UVPPD-measured velocity profile for untempered milk chocolate melt in processing pipe (25mm diameter) at 33°C; 5b: Radial shear stress function for untempered milk chocolate melt in processing pipe (25mm diameter) at 33°C [18]

Figure 6 shows the comparison of viscosity functions measured by UVPPD and an of-line rheometer for a 25% by volume of a bimodal mixture of 11 and 90 micron polyamide particles in rapeseed oil [19].

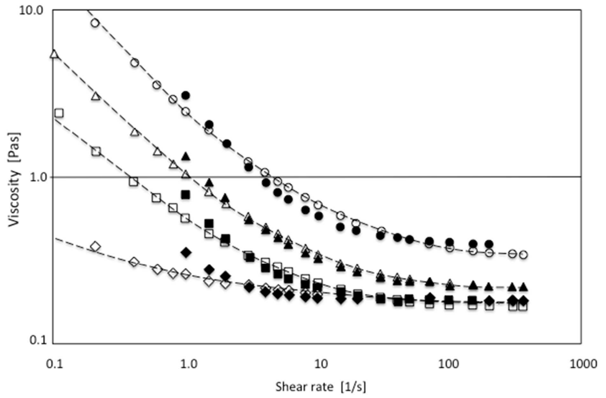


Figure 6: Variation of viscosity with shear rate in of suspensions of a constant total concentration of 25% by volume of a bimodal mixture of 11 and 90 micron polyamide particles in rapeseed oil. Open symbols: Data measured using an off-line rheometer (Dashed lines: Corresponding Sisko model fits. Filled symbols: UVP+PD gradient method results) [19].

An example for a high spatial resolution UVD (UVP)-measured velocity profile in a rheometric concentric cylinder gap using a 36 MHz transducer is demon-strated in fig. 7. The shown velocity profile indicates so-called vorticity bands in a concentrated wormlike micellar dispersion [20-22].

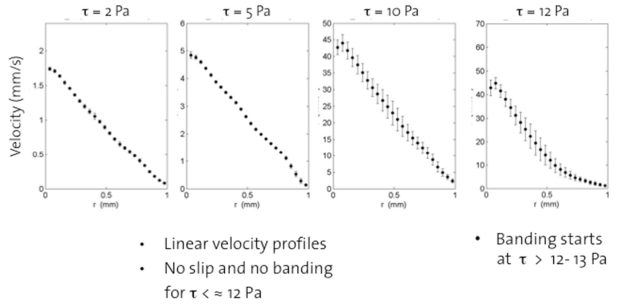


Figure 7: High spatial USD (UVP) resolution (ca. 40 micron) detection of vorticity band formation in rheometric concentric cylinder gap (gap with 1mm, fluid system: 40 mMol surfactant solution forming wormlike micelles) [20].

2.3.3 Coupled Structure Characterization - From a processing perspective there is crucial inte-rest to correlate rheological data with the fluid system microstructure in order to use related pro-cess-rheology-structure functions (PRS) for process control in food structure and related functionality tailoring. Concerned structural characteristics are e.g.: disperse phase concentration, particle / droplet size distribution, orientation and networking of structural components, phase changes. All of these also generally impact on (i) the velocity of sound and (ii) the US-attenuation. Fig. 8 shows the change in sound velocity for a crystallizing confectionery fat melt at different states in solids fat content, measured with a combined USD / USA measuring setup [23].

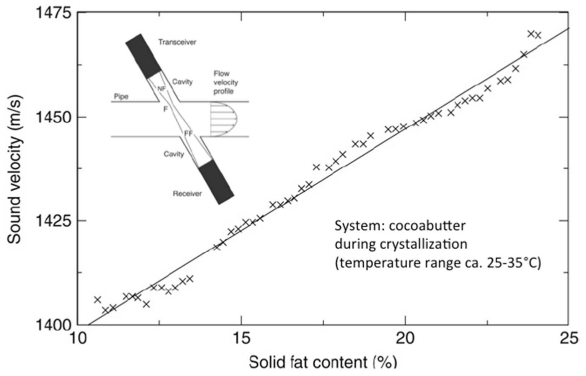
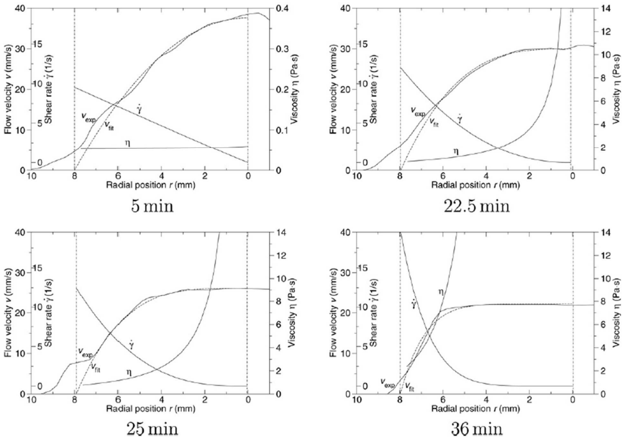


Figure 8: US-sound velocity/attenuation based measurement of fat crystal content in a crystallization process of cocoa butter (insert: USD/USA measuring cell setup) [23].

Based on such coupled process-rheology-structure information complex transient processes in food production like confectionery/fat crystallization can be controlled as exemplarily demonstrated in fig. 9 [22].



5 min 22.5 min 25 min 36 min

Figure 9: Transient radial distribution of shear rate γ˙ and viscosity η for the velocity distributions (full line: experimental profile, dashed line: fitted profile) in a cocoa butter crystallization process [23]

In order to get more detailed structural information like particle (here: fat crystal) size distribution Ultrasound Spectroscopy using information about the changes in sound velocity/attenuation at various US-frequencies can be applied. In a polydisperse system the extinction/attenuation of single particles overlay:

$$-\ln(I/I_0)_{fi} = \Delta I\, C_{PF} \int_{x\min}^{x\max} K(f_j, x)\, q_2(x)\, dx \qquad (4)$$

where: ΔI = layer thickness, K = extinction/attenuation coefficient, C_{PF} = area projection concentration, fi = US frequency

The integral in equation (4) can be substituted by a sum as a first approach and the project area concentration can be substituted by the particle concentration and the 1st momentum of the $q_2(xj)$ distribution:

$$-\ln(I/I_0)_{fi} \approx \Delta l\; 1.5 c_V (1/M_{1,2}) \sum_j K(f_i, x_j)\, q_2(x_j)\, \Delta x \quad (5)$$

If now extinction measurements are performed at various frequencies, this results in a linear equation system which can be solved by appropriate algorithms [24].
Within a commercial US-spectrometer (here e.g: OPUS by Sympatec AG, Clausthal-Zellerfeld, D) the attenuation at 31 frequencies is taken as one measure-ment within 60 s (typically). This leads to an attenuation spectrum. With the knowledge of the acoustic properties represented by the extinction function, the particle size distribution and solid concentration is calculated from the effective signal. The entire measuring range of OPUS covers 0.01 to 3,000 µm. The applied measuring range can be set according to the demands of the product and should not exceed a factor of 1,000 between the minimum and maximum size range (i.e. 1–1,000 µm for particulate food system applications). Figure 10 demonstrates the good agreement between sieve analysis and US-spectroscopic (OPUS) results for quartz particles [24]

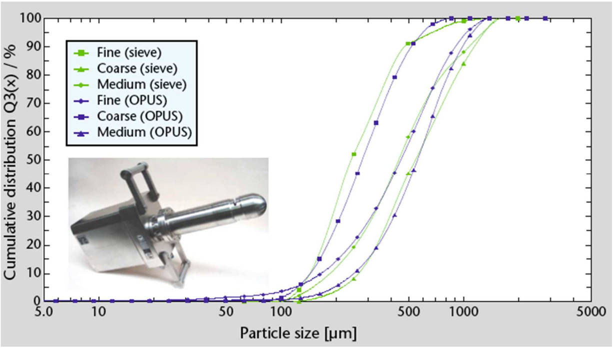


Figure 10: Typical comparability between OPUS and sieve analysis in terms of cumulative distributions from concentrated suspension (here: 30% vol. solids in water). Material: Quartz sand, coarse, medium, fine fraction [23].

2.4 Home processing/meal preparation (iv)

So far in home processing of food / meal preparation mostly high power ultrasound techniques for dispersing, extraction processing, tenderization and inactivation are applied. Low power ultrasound based measuring techniques detecting US-velocity and US attenuation patterns are suggested for texture measurements e.g. after cooking or baking processes [24]. Thus there is some similarity in US applications compared to chapter 2.2 dealing with harvesting of the food raw materials. USD based measurements are not yet found in this FVC domain (iv). However there may be a future perspective concerning the coupling of high power ultrasound applications with low power US measurements.

2.5 Eating and digestion of the food (v, vi)

The safe consumption of solid foods relies upon the intricate co-ordination of the masticatory apparatus. To produce a bolus of suitable particle size, internal cohesiveness and lubrication of the jaw, tongue and cheeks are employed to fragment, crush, shear and mix the ingested food in preparation for swallowing. Disparities in food characteristics (e.g. texture, juiciness and size), as well as subjects' individual chewing strategies decree the degree of mastication necessary before the optimum bolus properties have been attained for swallowing safely.
Ultrasonic echo-sonography was used to monitor tongue movements of each subject. The movement of the tongue was displayed by two imaging types: B- mode images, which showed a two-dimensional recording of the slice through the oral cavity (Fig. 2), and M-mode that depicted the movement of the tongue as a function of time [25-27]. From coupling B- and M-mode a spatio-temporal pattern e.g. of tongue motion can be received (see Figure 11). This provides a complementary information for the flow motion of the food in oral processing.

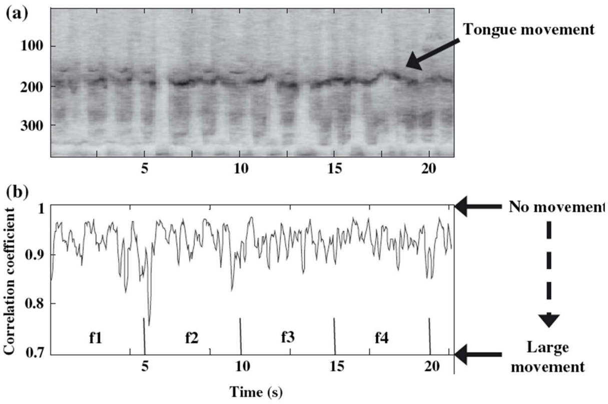
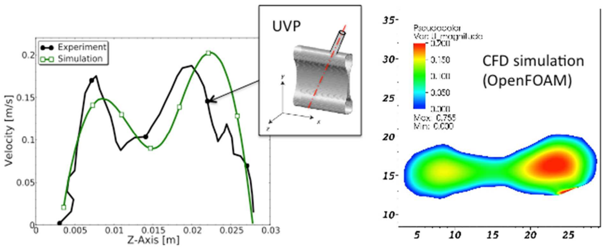


Figure 11: (a) M-mode image depicting the movement of the tongue as a f- unction of time generated from the middle slice of the B-mode video shown in Fig. 2. (b) Correlation coefficients calculated from adjacent columns in the image shown in (A) for four 5-s time periods [25]

Similar type of measurements by US-sonography are reported for the monitoring of swallowing and the related motion of the pharynx and esophagus [e.g.: 28]. An experimental model setup to study the flow in a collapsing elastic tube simulating the deformation and bolus flow in the human esophagus has been described in [28]. Figure 12 demonstrates related velocity profiles measured by USD and for comparison a CFD-simulated one taking the non-Newtonian rheological behaviour of a model food into account.
Ultrasonography is a versatile method that can be used to evaluate further antral contractility, gastric emptying, trans-pyloric flow, gastric configuration, intra-

gastric distribution of meals, gastric accommodation and strain measurement of the gastric wall. Advanced methods for endoscopic ultrasound, three-dimensional (3D) ultrasound, and tissue Doppler (Strain Rate Imaging) provide detailed information of the GI tract.

- Velocity profiles are compared at various cross-sections.



- Acceptable agreement between simulation and experiments.

Figure 12: USD-measured velocity profile in collapsed elastic esophagus-model tube and comparison with CFD simulated profile [29]

Food hypersensitivity reactions including gastrointestinal reactions due to food allergy can be visualized by ultrasonography and MRI. Development of multi-parametric and multi-modal imaging may increase diagnostic benefits and facilitate fusion of diagnostic and therapeutic imaging in the future. Ultrasonography can provide physiological, pathophysiological and biomechanical information to the clinician and constitutes an important tool in the diagnosis and follow up of large populations of patients [30].

A novel USD-based technique is the so-called Tissue Doppler imaging (TDI) which enables mapping of local tissue velocities, thus increasing the physiological information about moving walls [28]]. However, the point velocity of tissue does not differentiate between actively contracting and passively following tissue. Therefore, a Doppler method based on strain rate imaging (SRI) and estimation of relative strain was developed to enable this differentiation. In general terms, strain means tissue deformation as a function of applied force (stress) [30,31]. The temporal derivative of strain, i.e. the strain rate, is a measure of the rate of deformation. - Despite such advanced developments of the USD-based (3D-) US-sonography there is still only minor focus on the “food flow” aspects within the gastro-intestinal tract, which takes the interplay of the rheologically complex food in a partially digested state and its digestive disintegration and interaction with the GI-tissue dynamics into account.

Accordingly there has research work been started to address this area and combine in vivo US-Doppler velocimetry/US-sonography studies with an experimenttal fluid dynamics approach taking advanced in vitro model setups into account and complement this by numerical flow simulation (CFD).

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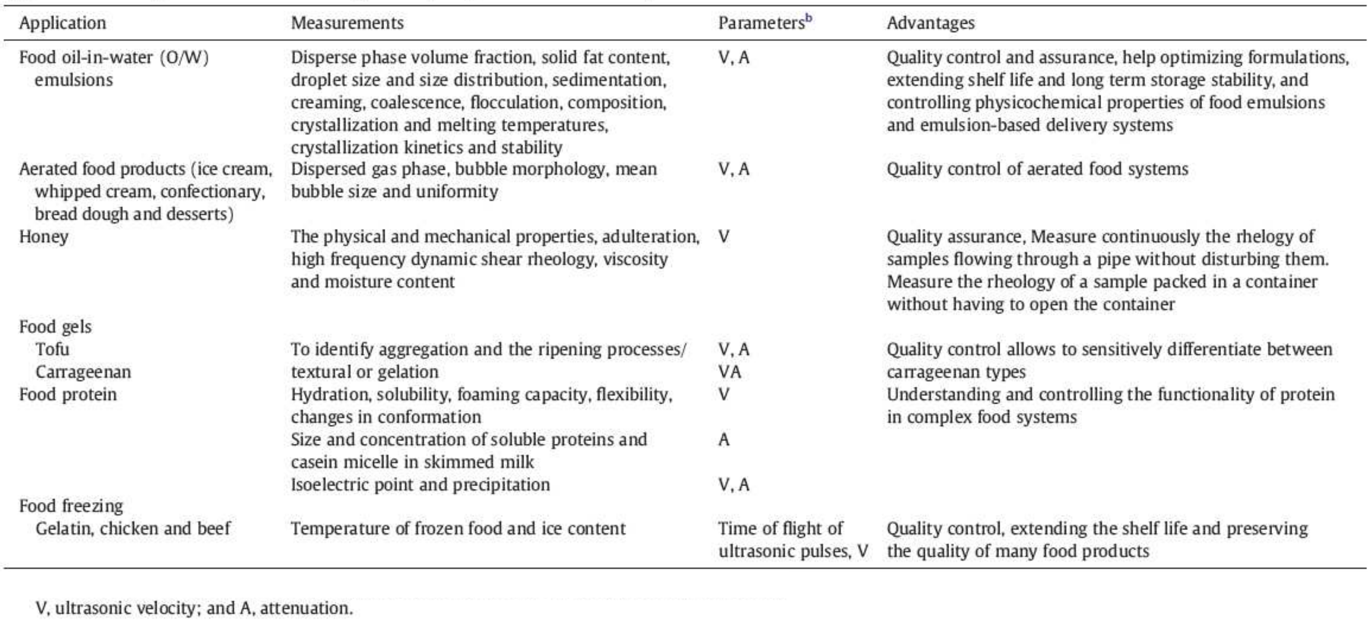
TABLE 1 :

Applications of low power ultrasound for analysis and quality control of selected food products [12]



Application	Measurements	Parameters[b]	Advantages
Food oil-in-water (O/W) emulsions	Disperse phase volume fraction, solid fat content, droplet size and size distribution, sedimentation, creaming, coalescence, flocculation, composition, crystallization and melting temperatures, crystallization kinetics and stability	V, A	Quality control and assurance, help optimizing formulations, extending shelf life and long term storage stability, and controlling physicochemical properties of food emulsions and emulsion-based delivery systems
Aerated food products (ice cream, whipped cream, confectionary, bread dough and desserts)	Dispersed gas phase, bubble morphology, mean bubble size and uniformity	V, A	Quality control of aerated food systems
Honey	The physical and mechanical properties, adulteration, high frequency dynamic shear rheology, viscosity and moisture content	V	Quality assurance, Measure continuously the rheology of samples flowing through a pipe without disturbing them. Measure the rheology of a sample packed in a container without having to open the container
Food gels			
Tofu	To identify aggregation and the ripening processes/	V, A	Quality control allows to sensitively differentiate between
Carrageenan	textural or gelation	VA	carrageenan types
Food protein	Hydration, solubility, foaming capacity, flexibility, changes in conformation	V	Understanding and controlling the functionality of protein in complex food systems
	Size and concentration of soluble proteins and casein micelle in skimmed milk	A	
	Isoelectric point and precipitation	V, A	
Food freezing			
Gelatin, chicken and beef	Temperature of frozen food and ice content	Time of flight of ultrasonic pulses, V	Quality control, extending the shelf life and preserving the quality of many food products

V, ultrasonic velocity; and A, attenuation.